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# EFFECTIVE GREEN AND AMPT PARAMETERS FOR TWO LAYERED SOILS

BY

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THESIS

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# ABSTRACT

Green-Ampt method is a physically based model for partitioning rainfall into surface runoff and infiltration. This method is widely used in infiltration practice because of its simplicity and the ease of obtaining required hydraulic soil properties. The method assumes that soil is homogeneous, therefore it is difficult to apply to layered soils. In this paper, simple procedures for applying Green-Ampt method to layered soils are examined both under steady and unsteady rain. For a given design storm, the maximum saturated depth of the top layer can be estimated. Because the uppermost layer controls the behavior until the wetting front reaches the boundary of the layers, if the thickness of the top layer is greater than maximum saturated depth, considering only the uppermost layer makes no difference in terms of infiltration process. However, if this is not the case, the bottom layer should be considered. To consider two-layered soils, overall effective Green-Ampt parameters of layered soils are estimated considering different parameters such as rainfall characteristics, the hydraulic properties of both layers, the thickness of the top layer and the maximum saturated depth. Runoff and infiltrated volumes with effective Green-Ampt parameters were compared with MIKE SHE simulation results based on Richards equation for different layer thicknesses, soil properties, and rainfall hyetographs. These results show that the proposed simple and quick procedures for estimating effective soil parameters show good agreement in terms of the volume of runoff and infiltration water. Therefore, this approach will help researchers and engineers to save time and effort dealing with layered soils using Green-Ampt method.

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# CHAPTER 1. INTRODUCTION

## 1.1. BACKGROUND

Infiltration is the water movement from the ground surface into the soil and a dominant process affecting surface runoff production. Infiltration process is caused by two major driving forces, gravity and capillary forces. These forces are related to the pore size of the soil. Infiltration through larger pore size is highly influenced by gravity force. On the other hand, capillary forces may play a major role in infiltration into very small pore size. However, soil is not always homogeneous, hence the infiltration process is very complicated and difficult to predict. There have been many efforts to understand infiltration process by empirical, experimental observations, analytical, theoretical and numerical solutions. However, many researchers and engineers still have some difficulties estimating infiltration process.

Broadly, surface-runoff generation process can be divided into two categories. One is infiltration excess runoff generation and the other is saturation excess runoff generation (Tarboton, 2003). Those two runoff generations can be observed on any soils or even at the same site depending on many variables such as the water input rate, hydraulic soil properties, initial depth to the water table and soil moisture. If the rate at which water is entering an area of land surface such as rainfall or run-on from adjacent areas is greater than the rate of infiltration, infiltration excess runoff generation occurs. Whereas, saturation excess occurs when the soil becomes completely saturated and this can be observed frequently where the groundwater table is shallow.

In this thesis, Green-Ampt method (Green and Ampt, 1911) is used for partitioning rainfall into runoff and infiltration water in two-layered soils. Green-Ampt method is a physically based model, widely used in infiltration practice because of its simplicity and ease of obtaining required hydraulic soil properties. The method assumes that soil is homogeneous with uniform antecedent moisture content under the ground surface. It also assumes a sharp wetting front exists, dividing upper saturated zone and lower unsaturated zone as infiltrated water moves down into the lower zone. Green-Ampt method is based on Darcy's law as a momentum equation as below.

$$f = -K_s \frac{\partial h}{\partial l} \qquad \frac{\partial h}{\partial l} = hydraulic\ gradient \tag{1}$$

If ponding depth at the surface is negligible, the infiltration rate (*f*) can be expressed as

$$f = K_s \frac{|\psi_f| + Z_f}{Z_f} \tag{2}$$

where $f$ is infiltration rate [L/T], $K_s$ is saturated hydraulic conductivity [L/T], $|\psi_f|$ is suction head at the wetting front [L] and $Z_f$ is the depth of the wetting front [L].

Also, for continuity, infiltration water (*F*) between ground surface and the wetting front can be defined as

$$F = Z_f(\theta_s - \theta_i) \tag{3}$$

where $F$ is infiltration water [L], $\theta_s$ is saturated moisture content [$L^3/L^3$] and $\theta_i$ is initial moisture content [$L^3/L^3$].

Rearranging equation (3) for $Z_f$ and substituting it into equation (2), the infiltration rate (*f*) become

$$f = K_s\left(1 + \frac{|\psi_f|(\theta_s - \theta_i)}{F}\right) \tag{4}$$

Equation (4) is well known Green-Ampt equation for estimating one-dimensional vertical infiltration rate.

Also, in this thesis, Richards equation (1931), which represents water movement in the unsaturated soils, is assumed to be the exact solution to compare with the simulation results by Green-Ampt method. Since Green-Ampt method is a simplified version of Richards equation that is known as the most accurate model for water movement when the unsaturated flow is dynamic (Leconte and Brissette, 2001; DHI, 2007b), it would be worthwhile to compare the two simulation results. Govindaraju et al. (1996) also pointed out that the Green-Ampt equation can be an alternative method to the Richards equation for the uniform, unsaturated soils.

The volumetric flux ($q$) for Richards equation is also obtained from Darcy's law. For 1D continuity equation will be

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} \tag{5}$$

Also, Darcy's law can be written as

$$q = -K(\theta)\frac{\partial h}{\partial z} = -K(\theta)\frac{\partial}{\partial z}(\psi + z) \tag{6}$$

Substituting equation (6) into equation (5) yields

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial\psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} \tag{7}$$

where $\theta$ is the volumetric soil moisture [$\mathrm{L}^3/\mathrm{L}^3$], $K(\theta)$ is the unsaturated hydraulic conductivity [L/T] and $\psi$ is pressure head [L].

Equation (7) is Richards equation for solving 1D transient water flow in the unsaturated soils. To solve the Richards equation, hydraulic conductivity function and soil moisture retention curve are needed. There are three standard forms of Richards equation, which are tension-based, $\theta$ -based, and mixed forms (Vasconcellos & Amorim, 2001). In this research, the tension-based model is used for Richards equation and this will be discussed in Chapter 3.

Runoff production is affected by many factors such as climate, topography, soil characteristics and human impact. In this study, we will focus on the effect of soil characteristics on surface runoff production. In particular, this study will focus on the effect of vertical heterogeneity on runoff. This is because, when a simple hydrologic model to estimate catchment's response to precipitation, it is difficult to apply Green-Ampt method to layered soils. Sometimes, to obtain simple estimation of water movement, only the top horizon of soil is considered for infiltration as a controlling horizon. However, the thickness of uppermost layer would vary considerably from site to site and the bottom layer of soil can be important for infiltration process depending on the storm events, soil characteristics and antecedent moisture content. For cases where the lower soils layer impacts the infiltration, considerable time and effort are required to develop a model that simulates the infiltration considering both soil layers. Thus, overall effective Green and Ampt soil parameters are necessary to apply Green-Ampt method to the layered soils.

Therefore, the aim of the thesis is to find simple procedures for obtaining effective Green-Ampt soil parameters for two-layered soils. A V-shaped catchment with a two-layered soil profile is developed using MIKE SHE (Abbott et al., 1986a; Abbott et al., 1986b; DHI, 2007). MIKE-SHE is an integrated catchment model and it can analyze most of the hydrologic aspects such as groundwater flow, evapotranspiration, surface water and recharge to the groundwater. MIKE SHE has a function for defining soil profile which allows soil profiles with different soil types and layer thicknesses. MIKE SHE also has options of Green and Ampt and Richards equation for subsurface flow. Thus, MIKE SHE simulation results based on Green-Ampt with effective soil parameters will be compared with MIKE SHE simulation results based on Richards equation to make sure if the proposed procedures are valid.

## 1.2. OBJECTIVE AND SCOPE OF RESEARCH

The purpose of this thesis is to present an approach to determine representative Green-Ampt parameters for two horizontal layered soils since subsurface soil system can be represented by layered soils. Therefore, the proposed method is to develop equivalent Green-Ampt parameters for a homogeneous soil that approximates the behavior of the two-layered soils. In this study, the scope is limited to two-layer soils and event modeling rather than continuous simulation. Also, root extraction and evapotranspiration process are not considered in the thesis. This is because during storm, precipitation, surface runoff and infiltration are more significant than evapotranspiration and thus evapotranspiration is often assumed to be negligible (Gulliver et al., 2010).

From an engineering perspective, if it is possible to obtain reasonable simulation results by Green-Ampt with effective soil parameters assuming homogeneous subsurface, a quick and simple method can represent the layered soils. To develop the proposed method, a V-shaped catchment that has a constant slope toward the center of a flow path has been made using MIKE SHE to estimate precipitation partitioning. More detailed information about the approach used to develop the proposed method will be presented in Chapter 3. MIKE SHE simulation based on Richards equation with two-layered soils with different thicknesses of top layer have been implemented. The simulation results were compared with the simulation results by Green-Ampt method using effective soil parameters determined using the proposed method.

Thus, in this thesis, simple procedures of obtaining Green-Ampt parameters for two-layered soils will be introduced considering rainfall characteristics, the hydraulic properties of both layers, the thickness of the top layer and the maximum saturated depth. The simulation results will be compared to MIKE SHE simulation based on Richards equation to validate the method. Even though the proposed procedures are limited to two-layered soils, the procedures can be applicable to both uniform and time-varying hyetograph. Therefore, the procedures would be useful for researchers and engineers who want to estimate runoff and infiltrated volume using Green-Ampt method for two-layered soils quickly and easily.

# CHAPTER 2. LITERATURE REVIEW

## 2.1. ESTIMATING SUCTION HEAD AT THE WETTING FRONT

To estimate Green-Ampt soil parameters, Rawl et al. (1983) presented average values of Green-Ampt parameters for different soil textures by analyzing approximately 5000 soil horizons across the United States. Based on Rawl et al. (1983)'s analysis, typical Green-Ampt parameters for various soil classes can be easily obtained. However, in this thesis, since MIKE SHE simulation based on Green-Ampt method will be compared to the simulation based on Richards equation, Green-Ampt soil parameters should be equivalent to soil characteristics of Richards equation in each layer. In other words, the Green-Ampt soil parameters should be determined from soil moisture retention or hydraulic conductivity curves of the soil. Especially, estimation of suction head at the wetting front ($\psi_f$) is more difficult than saturated hydraulic conductivity and initial moisture deficit. Therefore, in this chapter, several different methods to determine $\psi_f$ from soil hydraulic properties will be discussed.

Bouwer (1969) presented a way to determine $\psi_f$ from water retention curve. A constant value of $\psi_f$ should be taken as the water-entry pressure, $P_w$, because the soil above the wetting front is fully saturated with infiltrated water, based on an assumption of Green-Ampt method. Also, when water and air coexist in the soil pores, the water retention curve shows drying and wetting curves. The air-entry pressure of the water retention curve, $P_a$, can be obtained from the drying curve. Bouwer (1969) argues $P_w$ can be determined as about $0.5P_a$.

Merel-Seytoux and Khanji (1974) derived the following expression by accounting for air flow below the wetting front. Although this method has precise physical meaning, obtaining relationship between $k_{ra}$ and $h_c$ needs an extra effort.

$$\psi_f = \int_0^{h_{ci}} \frac{\frac{k_{rw}}{\mu_w}}{\frac{k_{rw}}{\mu_w} + \frac{k_{ra}}{\mu_a}} dh_c \tag{8}$$

where $k_{rw}$ and $k_{ra}$ are relative permeabilities [L/T] and $\mu_w$ and $\mu_a$ are dynamic viscosities [ML$^{-1}$T$^{-1}$] of water and air, respectively. $h_c$ is capillary pressure head [L] and $h_{ci}$ is initial capillary pressure head below the wetting front [L].

Mein and Farrell (1974) derived $\psi_f$ from hydraulic conductivity curve analytically and $\psi_f$, can be estimated as shown below by dividing the moisture content profile into horizontal discrete segment,

$$\psi_f = \int_0^{\psi_k} \frac{k(\psi)\mathrm{d}\psi}{K_s} \tag{9}$$

where $K_s$ is saturated hydraulic conductivity [L/T], $k(\psi)$ is unsaturated hydraulic conductivity [L/T] and $\psi_k$ is suction head at initial moisture content [L].

Since Green-Ampt method assumes $\psi_f$ is constant during infiltration, Mein and Farrell (1974) highlighted that they could obtain almost constant values of $\psi_f$ after surface ponding and the results of infiltration volumes using their method show good agreement. Neuman (1976) pointed out that Mein and Farrell (1974)'s derivation can be questioned on physical grounds. Neuman provided theoretical justification of equation (9) by using Philip's (1969) expression.

Also, among several ways to determine suction head at the wetting front from soil hydraulic properties, Ma et al. (2010a) show that the cumulative infiltration ($F$) simulated by Bouwer method (1969) is in better agreement with the measured data than Neuman method (1976). Thus, in this thesis, Bouwer method will be used to determine suction head at the wetting front for Green-Ampt infiltration.

## 2.2. GREEN-AMPT MODEL FOR LAYERED SOILS

In this chapter, previous studies on infiltration process into layered soil profiles in the literature are presented. There have been a lot of studies on infiltration process into multilayered soils over the past few decades. Especially, past studies on applying Green-Ampt infiltration for layered soils are investigated.

Moore and Eigel (1981) modified Green-Ampt and Mein-Larson (GAML) infiltration equations (Mein and Larson, 1973) to predict infiltration process for two-layered soil profiles. Moore and Eigel (1981) investigated coarse-over-fine and fine-over-coarse stratifications using two soils. The harmonic mean is used in the transmission zone of two-layered soils to calculate average hydraulic conductivity for Darcy's law to combine with the continuity equation of Green-Ampt. Also, several different constant rainfall intensities ($I$) which are greater than $K_s$ of two soils are used. The simulation results of modified GAML model are compared to both measured data and numerical model based on Richards equation with different thicknesses of the surface layers. For coarse-over-fine stratifications, time to ponding based on modified GAML is less than the results of the numerical model except for a few cases. Also, a modified GAML model underestimated cumulative infiltrated water ($F$) compared to both observed data and the numerical model in most of the cases. Although there are some discrepancies between modified GAML and the observed data, the errors between modified GAML and numerical model are acceptable. However, Kale and Sahoo (2011) pointed out that modified GAML model is only applicable under initial ponding condition.

Flerchinger et al. (1988) used an equation presented by Fok (1970) for infiltration rate into multilayered soils and derived an explicit solution for accumulated infiltration into layered soils by using a power series approximation to a logarithmic term with four dimensionless parameters. The explicit solution was also extended to predict infiltrated water for a discrete time step. Even though this solution is only valid for coarse-over-fine stratifications and steady storm event, it is acceptable in terms of accuracy.

Leconte and Brissette (2001) developed a conceptual model for one-dimensional vertical unsaturated water movement in two-layered soils which are coarse-over-fine stratifications based on the hypothesis of a sharp wetting front and a uniform pore pressure behind the wetting front. Also, the average hydraulic conductivity behind the wetting front is calculated by the harmonic mean. These assumptions allow Richards equation to be reduced to an ordinary differential equation and thus the equation can be solved with Runga-Kutta method. The results of the conceptual model with many soil types were compared to the results of numerical solution based on Richards equation and the conceptual model shows good agreement in terms of accumulated infiltration and average soil moisture in the upper layer under both simple and complex rainfall sequence.

Also, the simulation time required to run the conceptual model is 8-10 times less than the time required to run Richards equation.

Ma et al (2010) presented a modified Green-Ampt model by introducing a saturation coefficient, $S_e$, to describe the hydraulic conductivity and moisture content of wetted zone. $S_e$ is the ratio of measured moisture content to total saturated moisture content of the wetted zone and the value is calculated by an experiment with five-layered soil column. Also, $S_e$ is used to determine hydraulic conductivity at residual air saturation instead of using saturated hydraulic conductivity. This is because Ma et al (2010) stressed that pore spaces in wetted zone cannot be completely saturated with water because of entrapped air and thus using saturated hydraulic conductivity in the wetted zone is inappropriate. In the experiment with 300cm long layered soil column, the modified Green-Ampt model with $S_e$ was compared with traditional Green-Ampt method, numerical method based on Richards equation using HYDRUS-1D (Šimůnek et al., 2005) and measured data. Also, in this study, both Bouwer (1969) and Neuman (1976) methods are used to determine suction head at the wetting front and the modified Green-Ampt model with Bouwer method (1969) provided good results in terms of infiltration rate, cumulative infiltrated water and the wetting front movement compared to the measured data. However, the results of modified Green-Ampt model can be highly influenced by the accuracy of the saturation coefficient, $S_e$, which is not easy to obtain.

Liu et al (2008) derived a Green-Ampt for Layered Soils (GALS) model to estimate infiltration process for layered soils. They assumed that the infiltration flux in any layer behind the wetting front is equal for a short time period. An equation of infiltration capacity derived by Liu et al (2008) is identical to the derivations of Fok (1970). Also, they presented an implicit formula for the cumulative infiltration for layered soil column. To test the GALS model, three different cases are implemented, which are steady infiltration into layered soils with nonuniform soil water content, non-steady infiltration into layered soils with uniform soil water content and non-steady infiltration into the layered soil with nonuniform soil water content. The simulation results based on GALS model show good agreement compared to the observation data.

With all these methods discussed above, many of which show good agreement with a numerical solution based on Richards equation or measured data. However, most of the methods are difficult to apply in practical application since most of the methods modified the original Green-Ampt equation and those equations are complicated to apply. In this thesis, the original Green-Ampt method is used for estimating of infiltration into two-layered soils. Maximum saturated depth will be introduced in Chapter 3 and this definition will be used to estimate overall effective hydraulic conductivity of two layers. Using original Green-Ampt method with the effective Green-Ampt soil parameters of two-layered soils makes the estimation of infiltrated water more quickly and simply.

# CHAPTER 3. METHODOLOGY

## 3.1. MODEL SETUP USING MIKE SHE

### 3.1.1. V-Shaped Catchment

A virtual V-shaped catchment has been made to run the MIKE SHE (DHI Software, 2007a, 2007b). A V-shaped catchment model is the standard case to understand the partitioning of rainfall into runoff and infiltration in hillslope hydrology (Phong et al., 2015). The model domain is composed of 92×92 square cells and each cell size is equal to 10m. However, grid cells on the model boundary must be assigned in the model domain so that the number of interior grid cells is 90×90. Hence, the actual area of the catchment is 0.81km$^2$. The topography and top view of the model domain are shown in Figure 3.1 and Figure 3.2. An impervious channel with slopes in x-direction and y-direction of 0% and 0.02%, respectively, and with a width of 100m is assigned at the center of the domain. There are two different planes toward the channel and the slope of the planes in x-direction and y-direction are 0.05% and 0% respectively with a soil depth of 5m in Z-direction. The description of the domain is summarized in Table 3.1.

**TABLE 3.1 MODEL DOMAIN AND GRID**

| Area [km$^2$] | Cell size [m] | Number of cell X | Number of cell Y | Soil depth in Z [m] | Outside Boundary condition |
|---|---|---|---|---|---|
| 0.81 | 10 | 90 (92) | 90 (92) | 5 | impervious |

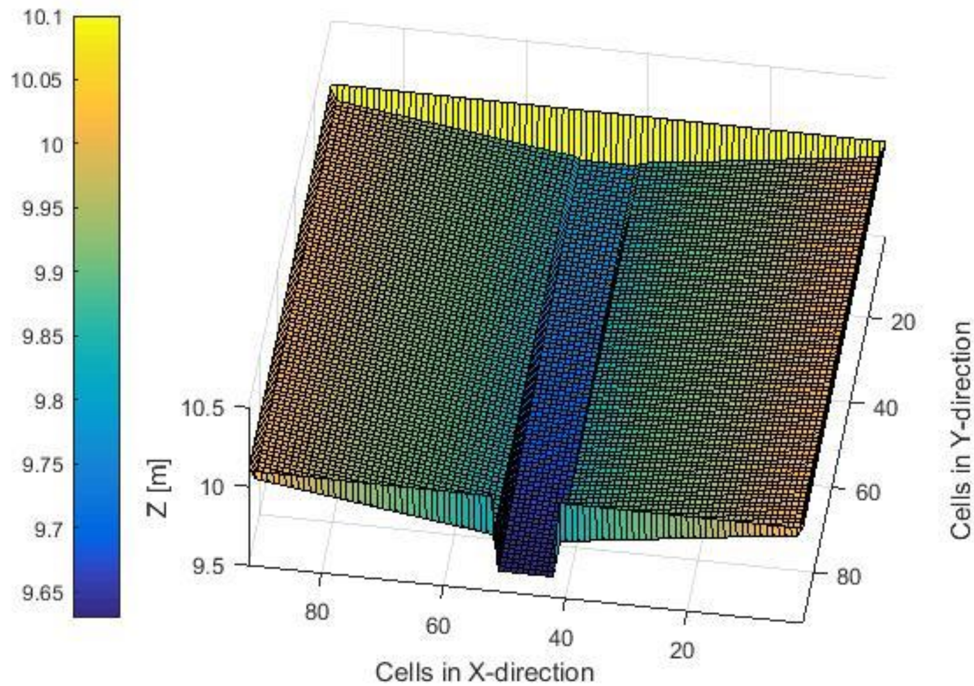


**FIGURE 3.1 TOPOGRAPHY OF MODEL DOMAIN**

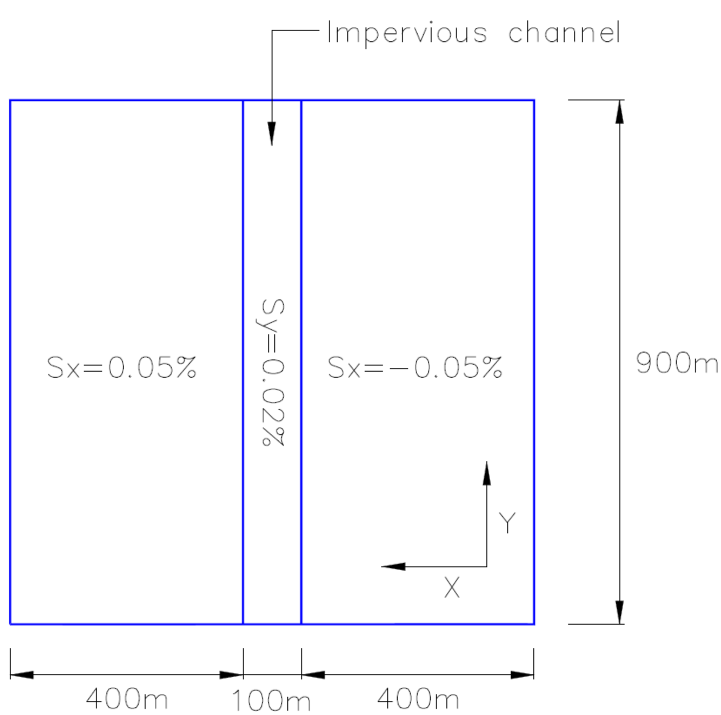


**FIGURE 3.2 TOP VIEW OF MODEL DOMAIN**

The spatial distribution of precipitation is uniform in the entire domain and partitioning of precipitation defining soil profile in Z-direction with different soil types and layer thicknesses will be simulated using MIKE SHE. This domain can represent a small catchment with a gentle slope and the slope will allow simulating Green-Ampt method with a widely accepted assumption that ponded depth at the ground surface is small or negligible for surface water hydrology problems (Chow, 1964). Hence, MIKE SHE simulations with the model domain can show that the proposed method to determine effective Green-Ampt parameters for two-layered soils can be applied to a small catchment scale.

### 3.1.2. Subsurface Flow

Subsurface flow is a dominant process for partitioning of rainfall into infiltration and surface runoff production. Since during infiltration process, gravity plays a major role in unsaturated flow, MIKE SHE simulation based on Richards equation is assumed to be vertically one-dimensional flow in unsaturated zone. To simulate two layered soils, Richards equation, which is known as the most accurate method for water movement in unsaturated zone (Leconte and Brissette, 2001; DHI, 2007b) is chosen. Because root extraction and evapotranspiration process are not considered in the thesis, Richards equation can be written as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} \tag{10}$$

where $\theta$ is the volumetric soil moisture [$L^3/L^3$], $K(\theta)$ is the unsaturated hydraulic conductivity [L/T], $\psi$ is pressure head [L], $z$ is the elevation above a vertical datum [L] and $t$ is time [T].

Based on the DHI software manual (2007b), the concept of soil water capacity, $C$, which is the slope of the soil water retention curve is defined as

$$C = \frac{\partial \theta}{\partial \psi} \tag{11}$$

Then, Richards equation can be re-written as

$$C\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} \tag{12}$$

This is the tension-based version of full Richards equation. The van Genuchten (1980) model is used to determine the soil moisture retention curve, $\theta(\psi)$, and hydraulic conductivity of unsaturated soils, $K(\psi)$, based on soil hydraulic properties as shown in Equation (13) and (14).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^m} \tag{13}$$

$$K(\psi) = \frac{K_s((1 + |\alpha\psi|^n)^m - |\alpha\psi|^{n-1})^2}{(1 + |\alpha\psi|^n)^{m(l+2)}} \tag{14}$$

where $\psi$ is suction head [L], $\alpha$ is an empirical constant as the inverse of the air entry value [$L^{-1}$], *n* is a measure of the pore-size distribution (*n*>1), *m* is 1-1/*n* and $l$ is shape factor (=0.5).

Needed parameters of the model for USDA textural soil classification are provided by Carsel and Parrish (1988) and those values are shown in Table 3.2. The values are used for MIKE SHE model setting.

TABLE 3.2 TYPICAL PARAMETER VALUES OF VAN GENUCHTEN MODELS (CARSEL AND PARRISH, 1988)

| Texture Class | $\theta_r$ | $\theta_s$ | $\alpha$ (1/cm) | $n$ | $K_s$ (cm/day) |
|---|---|---|---|---|---|
| Sand | 0.045 | 0.43 | 0.145 | 2.68 | 712.8 |
| Loamy sand | 0.057 | 0.41 | 0.124 | 2.28 | 350.2 |
| Sandy loam | 0.065 | 0.41 | 0.075 | 1.89 | 106.1 |
| Loam | 0.078 | 0.43 | 0.036 | 1.56 | 24.96 |
| Silt | 0.034 | 0.46 | 0.016 | 1.37 | 6 |
| Silt loam | 0.067 | 0.45 | 0.02 | 1.41 | 10.8 |
| Sandy clay loam | 0.1 | 0.39 | 0.059 | 1.48 | 31.44 |
| Clay loam | 0.095 | 0.41 | 0.019 | 1.31 | 6.24 |
| Silty clay loam | 0.089 | 0.43 | 0.01 | 1.23 | 1.68 |
| Sandy clay | 0.1 | 0.38 | 0.027 | 1.23 | 2.88 |
| Silty clay | 0.07 | 0.36 | 0.005 | 1.09 | 0.48 |
| Clay | 0.068 | 0.38 | 0.008 | 1.09 | 4.8 |

Note that for the simulation of overland flow, finite difference method using the diffusive wave approximation of Saint Venant equations is chosen in MIKE SHE.

### 3.1.3. Storm events

A variety of storm events are used as input to the MIKE SHE model simulations. First, steady rain will be considered with different rainfall intensity and duration. Rainfall intensity ($I$) can be divided into two cases depending on the saturated hydraulic conductivity ($K_s$) of top layer. One is the case where the rainfall intensity is greater than $K_s$ of the top layer, and the other is the case where the rainfall intensity is less than $K_s$ of the top layer. The two cases will be investigated for determining maximum saturated depth of top layer and effective Green-Ampt soil parameters of two layers.

Second, the model is run with unsteady rain events as well. For the time distribution of rainfall, Yen-Chow hyetograph (Yen & Chow, 1980) is selected. The Yen-Chow hyetograph is a non-dimensional triangular model that is often used as a design storm hyetograph. The peak rainfall intensity depends on the total depth of rainfall and its duration and it is known as a feasible method. Therefore, to simulate the model under unsteady rain, eight different Yen-Chow hyetographs will be added to consider different circumstances.

## 3.2. TWO-LAYERED SOILS

### 3.2.1. Selecting Soil Texture for Two Layered Soils

Two-layered soils are implemented for MIKE SHE simulation by Richards equation. An upper layer that has a coarse texture with relatively high hydraulic conductivity overlies a bottom layer that has lower hydraulic conductivity.

For the two-layered simulations, loam and clay loam are selected as the top and bottom layer, respectively, and each layer is assumed to be homogeneous. Figure 3.3 and Figure 3.4 represent the soil moisture retention and hydraulic conductivity curves of the top layer and bottom layer, respectively. Note that two-layered soils are used only for the simulation by Richards equation, while the entire subsurface will be assumed to be homogeneous for simulation by Green-Ampt method using effective soil parameters determined using the proposed method.

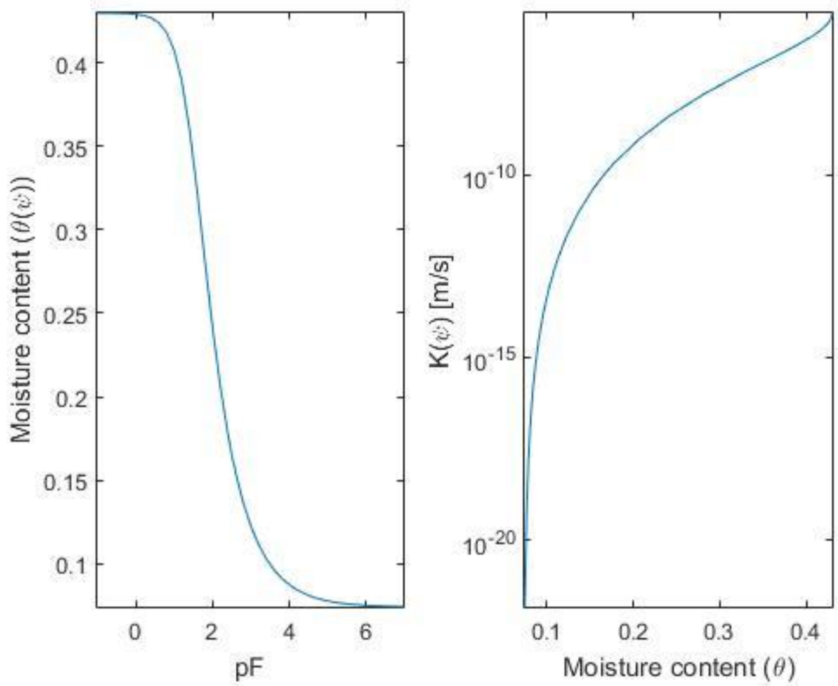


**FIGURE 3.3 SOIL MOISTURE RETENTION AND HYDRAULIC CONDUCTIVITY CURVES OF LOAM ($\mathbf{pF = \log_{10}(-100\psi)}$)**

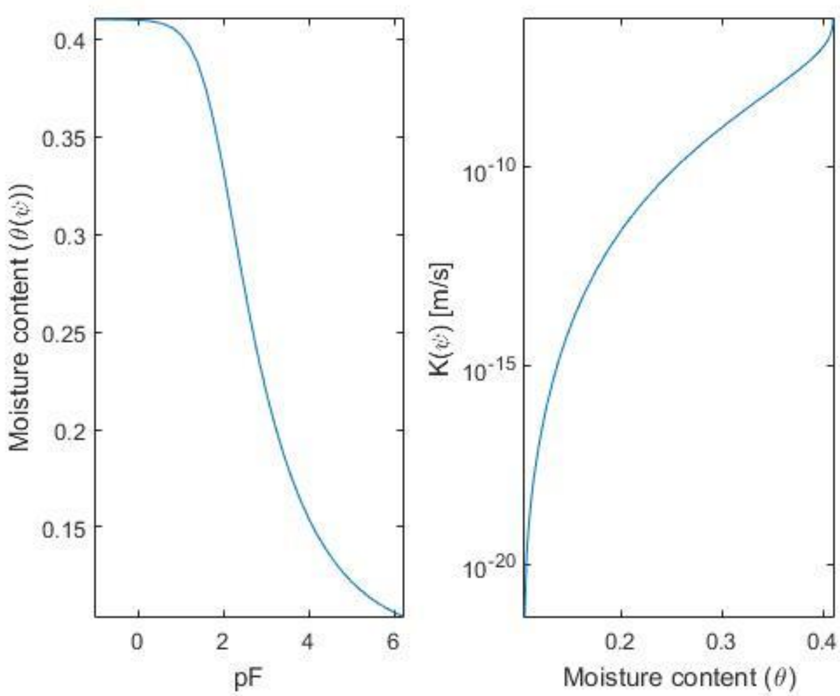


**FIGURE 3.4 SOIL MOISTURE RETENTION AND HYDRAULIC CONDUCTIVITY CURVES OF CLAY LOAM ($\mathbf{pF = \log_{10}(-100\psi)}$)**

To estimate overall effective Green-Ampt parameters, the parameters for each layer are needed. The Green-Ampt parameters for each layer can be obtained by soil moisture retention or hydraulic conductivity curves. The $K_s$ of each layer can be taken directly from the conductivity curve at saturated moisture content. Also, as discussed in Chapter 2.1, Bouwer method (1969) is used in this thesis and following Bouwer's method, $\psi_f$ at the wetting front can be estimated as $0.5P_a$. ($P_a$ is air-entry value of the water retention curve.)

Selected soil texture for both layers and calculated Green-Ampt parameters are listed in Table 3.3. Note that $\theta_s$ is saturated moisture content, $\theta_i$ is initial moisture content and $\theta_r$ is residual moisture content.

**TABLE 3.3 SOIL CHARACTERISTICS FOR GREEN AND AMPT OF TWO LAYERS**

| **Layer** | **Soil texture** | $K_s$ **[mm/hr]** | $\psi_f$ **[m]** | $\theta_s$ | $\theta_i$ | $\theta_r$ |
|---|---|---|---|---|---|---|
| Top | Loam | 9.53 | 0.05 | 0.43 | 0.16 | 0.078 |
| Bottom | Clay loam | 1.91 | 0.08 | 0.41 | 0.19 | 0.095 |

### 3.2.2. Threshold Depth of Top Layer ($Z_{threshold}$)

Before estimating overall effective Green and Ampt parameters for two or more horizontal layers, first we should consider how deep the infiltration water ($F$) would reach for a given storm event to decide whether the bottom layer should be considered or not. Thus, the threshold depth of top layer ($Z_{threshold}$) is defined here as a calculated saturation thickness of a soil with the upper layer properties for a given storm event. This definition of $Z_{threshold}$ is used because the uppermost layer controls the behavior until it is fully saturated or wetting front reaches the boundary of the layers during a given rain event. If the upper layer is not completely saturated, under the assumptions of the Green-

Ampt approach, the bottom layer does not affect the infiltration. These phenomena are observed through laboratory experiments by Hill (1992) and Deliman (1994), who showed that infiltration into the bottom layer does not begin until the top layer is fully saturated. Hence, to evaluate whether to consider the bottom layer or not, $Z_{threshold}$ should be estimated in advance. That is, if the depth of top layer is greater than $Z_{threshold}$, taking only top layer for infiltration modeling makes no difference for estimating infiltration process regardless of the bottom layer. Therefore, estimating $Z_{threshold}$ is required prior to the simulation.

To calculate $Z_{threshold}$, infiltration water ($F$) from given storm event should be estimated first. Hence, the procedure of estimating infiltration water ($F$) will be presented under both steady and unsteady rain assuming top layer has enough depth to absorb water from given event.

1) Steady rain

If the surface water input rate is constant, there are two possible cases in terms of infiltration process. One is the case that rainfall intensity ($I$) is less than the saturated hydraulic conductivity ($K_s$), and the other is the case that rainfall intensity is greater than $K_s$.

- Case 1: $I < K_s$

In this case, infiltration rate (f) will be equal to rainfall intensity with an assumption that the depth of the top layer is infinite, which is the case that top layer has enough pore space to absorb the water from given event so that saturation excess overland flow does not occur. Thus, if the top layer has deep enough, all rainfall should flow through the soil in the top layer. Therefore, infiltration water ($F$) would be,

$$F = I \times t \tag{15}$$

where $F$ is cumulative infiltration [L], $I$ is water input rate [L/T] and $t$ is duration of storm event [T].

- Case 2: $I > K_s$

When $I > K_s$, infiltration rate ($f$) should be less than or equal to infiltration capacity ($f_c$) or rainfall intensity ($I$) and infiltration excess would occur if rainfall intensity exceeds infiltration capacity. Mailapalli et al. (2009) proposed an explicit solution of the Green-Ampt equation for estimating infiltration water ($F$) based on a nonstandard explicit integration algorithm (EIA) developed by Ramos (2007). The EIA solution of cumulative infiltration shows good agreement compared to measured data in terms of accuracy.

However, Mein and Larson (1973) introduced two-stage Green and Ampt infiltration model under steady rain. They argued that infiltration process can be divided into two stages. Before surface ponding, infiltration rate should be equal to rainfall intensity which means all rainfall is soaking into the ground and after that, infiltration excess occurs because rainfall intensity is greater than infiltration capacity. Thus, following Mein and Larson (1973)'s argument, the proposed approach modifies the explicit solution of the Green-Ampt equation proposed by Mailapalli et al. (2009) to consider ponding time and infiltration water at surface ponding.

Infiltration water at ponding $F_p$ is

$$F_p = I \times t_p \tag{16}$$

Also, at surface ponding, infiltration capacity should be equal to rainfall intensity.

$$I = f_p = K_s\left(1 + \frac{\psi_f(\theta_s - \theta_i)}{F_p}\right) = K_s\left(1 + \frac{\psi_f(\theta_s - \theta_i)}{I \times t_p}\right) \tag{17}$$

Thus, the ponding time $t_p$ can be calculated by

$$t_p = \frac{\psi_f(\theta_s - \theta_i)}{I}\left(\frac{K_s}{I - K_s}\right) \tag{18}$$

Now, $F_p$ and $t_p$ can be used for estimating infiltration water. Using $F_p$ and $t_p$, cumulative infiltrated water can be estimated by modifying the explicit solution proposed by Mailapalli et al. (2009). A simple modified explicit function of Green-Ampt algorithm is shown below.

Step 1 : Input the values of $K_s$, $\psi_f$, $\theta_s$, $\theta_i$, $h$, $T_{\max} = t_d - t_p$ and $n$(=0).

Step 2 : Input the initial value of $F_n$ (=$F_p$)

Step 3 : Estimate value of $F_{n+1}$ at time $t$ (= $(n+1)h$) using equation (19) until $t \leq T_{max}$ (= $t_d - t_p$), otherwise, terminate the program.

$$F_{n+1} = F_n + \frac{2hK_s\left(1 + \frac{(\psi_f(\theta_s - \theta_i))}{F_n}\right)}{2 - h\left(-\frac{K_s\psi_f(\theta_s - \theta_i)}{F_n^2}\right)} \tag{19}$$

where $F$ is infiltration water [L], $K_s$ is saturated hydraulic conductivity [L/T], $\psi_f$ is suction head at wetting front [L], $\theta_s$ is saturated moisture content [$L^3/L^3$], $\theta_i$ is initial moisture content $[L^3/L^3]$ $h$ is step size (using 0.1min is recommended (Mailapalli et al., 2009)) and $n$ is step.

According to Mailapalli et al. (2009), using small number for initial value of $F_n$ is recommended and $T_{\max}$ for the program is the total duration of storm event $(t_d)$. In this thesis, instead of using those values, calculated $F_p$ will be used as initial value of $F_n$ and $t_d - t_p$ will be used for $T_{\max}$. Note that a hydraulic conductivity at residual air saturation, $K_e$ $(= 0.5K_s)$, was used instead of $K_s$ in the original explicit solution proposed by Mailapalli et al. (2009). This is because, the soil pores cannot be fully saturated with water and thus using $K_e$ is recommended because of entrapped air (Van Mullem (1991), Maidment (1993)). However, because a two-phase flow model will not be incorporated into MIKE SHE simulation based on Richards equation and the simulation results based on Green-Ampt method will be compared to the simulation results based on Richards equation, $K_s$ will be used in this thesis instead of $K_e$.

2) Unsteady rain

To estimate infiltration water under unsteady rain, Yen-Chow hyetograph (Yen & Chow, 1980) is chosen. According to Yen-Chow (1980), even though this hyetograph is a simple triangular model, it can reflect well on most of the natural storm event and preserve the volume and first moment of rain. In this thesis, the peak of rainfall intensity will be at 3/8 of the duration of rainfall. Therefore, if the volume of design storm is given, peak intensity $(I_k)$ and the time at peak $(t_k)$ will be

$$I_k = \frac{V}{t_d} \times 2 \tag{20}$$

$$t_k = \frac{3}{8} \times t_d \tag{21}$$

where $V$ is volume of rainfall [L], $t_d$ is duration of the event [T].

In contrast with steady rain, infiltrated water cannot be easily determined for the unsteady rain because rainfall intensity is changing over time. However, if ponding time could be estimated, infiltrated water also could be estimated under Yen-Chow hyetograph. Because of the hyetograph's simplicity, a linear equation of rainfall intensity over time can be easily obtained until its peak intensity by

$$I_t = \frac{I_k}{t_k} \times t \tag{22}$$

where $I_t$ is rainfall intensity over time [L/T], $I_k$ is peak intensity [L/T], $t_k$ is the time at peak [T] and $t$ is time [T].

At surface ponding, rainfall intensity at ponding ($I_p$) should be identical to the infiltration capacity at ponding ($f_p$) and thus this relationship can be expressed by

$$I_p = f_p = K_s \left(1 + \frac{\psi_f (\theta_s - \theta_i)}{F_p}\right) \tag{23}$$

where $I_p$ is rainfall intensity at ponding [L/T], $f_p$ is infiltration capacity at ponding [L/T] and $F_p$ is infiltration water at ponding [L].

Since the infiltration capacity is greater than the rainfall intensity before ponding begins, infiltrated water at ponding ($F_p$) should be integral of the rainfall intensity over time.

$$F_p = \int_0^t \frac{I_k}{t_k} t dt = \frac{1}{2} \frac{I_k}{t_k} t^2 \tag{24}$$

Substituting $F_p$ into equation (23) yields

$$\frac{I_k}{t_k} \times t = K_s \left(1 + \frac{2t_k \psi_f (\theta_s - \theta_i)}{I_k t^2}\right) \tag{25}$$

where $I_k$ is peak intensity [L/T], $t_k$ is the time at peak [T], $t$ is time [T], $K_s$ is saturated hydraulic conductivity [L/T], $\psi_f$ is a suction head at the wetting front [L], $\theta_s$ is saturated moisture content [L3/L3] and $\theta_i$ is initial moisture content [L3/L3].

Now, there is the only unknown variable $t$ and an intersecting point of two equations should be the time at ponding ($t_p$) and then $F_p$ can also be calculated by using equation (24). Note that if there is no intersecting point in equation (25), surface ponding does not occur for a given storm event so that all rainfall will infiltrate into the soil.

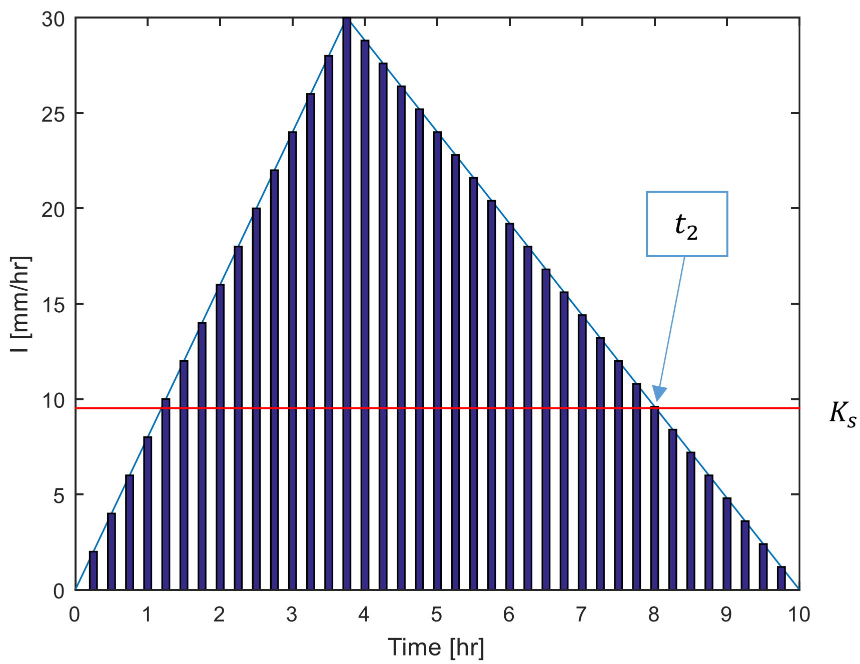


**FIGURE 3.5 TYPICAL YEN-CHOW HYETOGRAPH WITH $K_s$ OF THE TOP LAYER ($V$=150MM, $t_d$=10HR)**

Figure 3.5 shows one example of Yen-Chow hyetograph (V=150mm, $t_d$=10hr). The straight red line represents $K_s$ of the top layer and $t_2$ is defined as the second intersecting point between the hyetograph and the red line. It is assumed that rainfall excess will occur until the time $t_2$ and after time $t_2$, all rainfall will infiltrate into the soil. With these assumptions, infiltration water (F) until the time $t_2$ can be estimated similarly to the procedure using equation (19) which is a modified explicit function of Green-Ampt method. The only difference here is $T_{\max}$ which should be $t_2 - t_p$. After the time $t_2$, the infiltration rate is greater than rainfall intensity so that all rain will soak into the soil. The procedure of estimating infiltrated water under Yen-Chow hyetograph is shown in Table 3.4.

**TABLE 3.4 ESTIMATED INFILTRATED WATER UNDER YEN-CHOW HYETOGRAPH**

| **Time** | **Estimation of infiltrated water (*F*)** |
|---|---|
| $0$ - $t_p$ | $F_p = \frac{1}{2}\frac{I_k}{t_k}t_p^2$ |
| $t_p$ - $t_2$ | $\mathrm{F_{n+1}} = F_n + \frac{2hK_s\left(1+\frac{(\psi_f(\theta_s-\theta_i)}{F_n}\right)}{2-h\left(-\frac{K_s\psi_f(\theta_s-\theta_i)}{F_n^2}\right)}$<br>Step 1 : Input the values of $K_s$, $\psi_f$, $\theta_s$, $\theta_i$, $h$ (=0.1m), $T_{\max} = t_2 - t_p$ and $n$(=0).<br>Step 2 : Input the initial value of $F_n$ (=$F_p$)<br>Step 3 : Estimate value of $\mathrm{F_{n+1}}$ at time $t$ $(= (n+1)h)$ using equation (19) until $t \le T_{max}$ $(= t_2 - t_p)$, otherwise, terminate the program. |
| $t_2$ ~ $t_d$ | $F_2(t) = \int_{t2}^{t_d} I(t)dt$ |
| Total $F$ | $F = F_{n+1} + F_2$ |

3) Estimation of the maximum saturated depth ($Z_{threshold}$)

Estimating infiltration water ($F$) under steady and unsteady rain has been examined. Once $F$ for a given storm is estimated, the maximum saturated depth, $Z_{threshold}$, of the top layer can be obtained by assuming the homogeneous top layer,

$$Z_{threshold} = \frac{F}{\theta_s - \theta_i} \tag{26}$$

where $Z_{threshold}$ is threshold depth of top layer [L], $\theta_s$ and $\theta_i$ are saturated and initial moisture content, respectively [$L^3/L^3$].

After obtaining $Z_{threshold}$, we can evaluate whether the bottom layer does affect the infiltration for a given storm. If $Z_{threshold}$ is greater than depth of the top layer, bottom layer should be considered because the top layer will be fully saturated before the end of the storm and infiltration into the bottom layer would begin during the storm. On the other hand, if $Z_{threshold}$ is less than or equal to the depth of the top layer, the upper layer would not be completely saturated, and thus using soil characteristics of the top layer to estimate infiltration process should be fine for the given storm event. Figure 3.6 shows the flow chart of a process for dealing with layered soils depending on the estimation of $Z_{threshold}$.

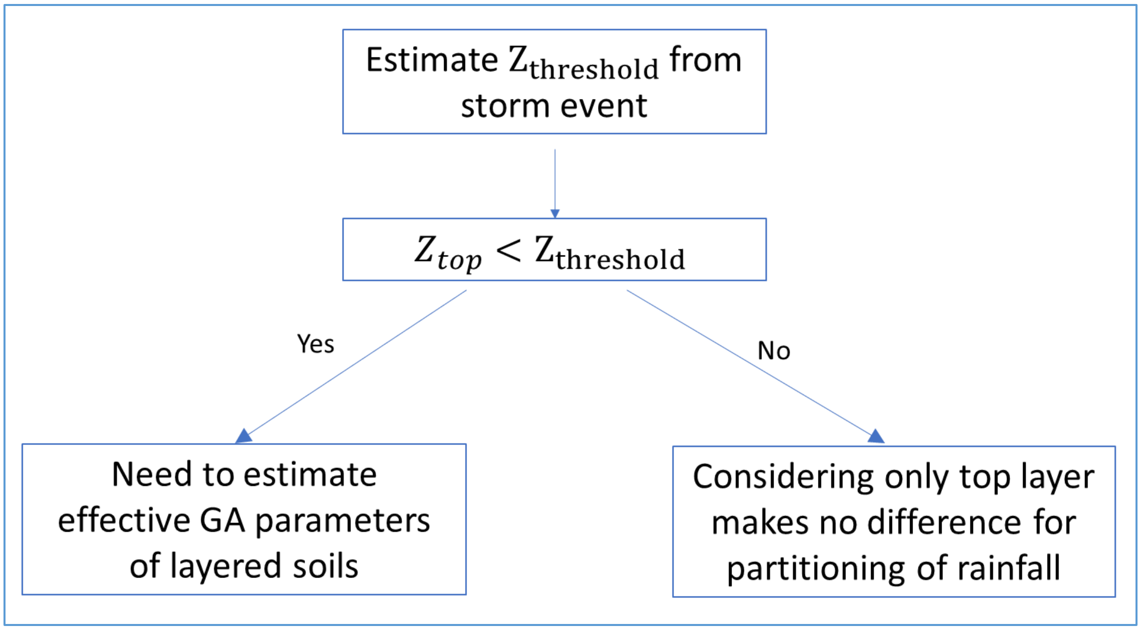


**FIGURE 3.6 FLOW CHART OF A PROCESS FOR DEALING WITH LAYERED SOILS**

### 3.2.3. Effective Green-Ampt Soil Parameters

If calculated $Z_{threshold}$ is greater than the depth of top layer ($Z_{top}$), a simple process for obtaining effective Green-Ampt parameters for two layered soils is needed. There are three hydraulic soil parameters needed to simulate Green-Ampt method, which are saturated hydraulic conductivity ($K_s$), suction head at the wetting front ($\psi_f$) and initial moisture deficit ($\Delta\theta = \theta_s - \theta_i$). Among those parameters, Weiss and Gulliver (2015) pointed out that the range of $\psi_f$ and $\Delta\theta$ are much less than that of $K_s$, which ranges over several orders of magnitude based on Green and Ampt parameters examined by Rawls et al. (1983). Dagan and Bresler (1983) also stressed that $K_s$ has much more impact on infiltration process than any other soil parameters because of its great deal of variability. Thus, in the thesis, average values of $\psi_f$ and $\Delta\theta$ are used as the effective parameters for two layers and a way to obtain a representative $K_{eff}$ of two soil textures will be closely examined.

To estimate $K_{eff}$ of two soils, two simple equations will be introduced considering $Z_{threshold}$ and the depth of the top layer. Since $Z_{threshold}$ of the top layer can be estimated for a given storm event, boundary conditions can be obtained. Under the steady rain, three different cases can be considered in terms of rainfall intensity.

- Case 1: $I > K_s$

When the rainfall intensity is greater than $K_s$ of the top layer, simple boundary conditions can be obtained by considering $Z_{threshold}$ and the thickness of the top layer.

$$Z_{top} = Z_{threshold} \quad --\rightarrow \quad K_{eff} = K_{s\_top} \tag{27}$$

$$Z_{top} = 0 \quad --\rightarrow \quad K_{eff} = K_{s\_bottom} \tag{28}$$

where $Z_{top}$ is thickness of the top layer, $K_{s\_top}$ is $K_s$ of the top layer and $K_{s\_bottom}$ is $K_s$ of the bottom layer.

If the depth of the top layer is approaching to $Z_{threshold}$, using $K_s$ of the top layer as an overall effective hydraulic conductivity of the two layers ($K_{eff}$) is justifiable because infiltration into the bottom layer would not occur. Also, if the depth of the top layer is approaching to zero, $K_s$ of the bottom layer become overall $K_{eff}$ of two layers since the soil will be uniform consisting of only the bottom layer. With those boundary conditions, a simple linear equation (29) is obtained and $K_{eff}$ can be calculated depending on the depth of the top layer ($Z_{top}$). The equation (29) is simple; however, it involves not only the information about the depth of the top layer but also the history about given rainfall characteristics, because when $Z_{threshold}$ was calculated, both rainfall intensity and its duration were considered to calculate infiltration water (*F*).

$$K_{eff} = \frac{K_{s\_top} - K_{s\_bottom}}{Z_{threshold}} \times Z_{top} + K_{s\_bottom} \tag{29}$$

where $K_{eff}$ is an overall effective saturated hydraulic conductivity of two layered soils [L/T], $K_{s\_top}$ and $K_{s\_bottom}$ are saturated hydraulic conductivities of top layer and bottom layers, respectively, [L/T] and $Z_{top}$ is an actual depth of the top layer [L].

- Case 2: $K_{s\_bottom} < I < K_{s\_top}$

In this case, one boundary condition should be adjusted compared to the Case 1. If the depth of the top layer is approaching to $Z_{threshold}$, actual infiltration rate (*f*) should be less than $K_s$ of the top layer because $f = I$ during the event. Here, $K_{pseudo}$ of the top layer is introduced as a pseudo value of saturated hydraulic conductivity of the top layer. Since actual infiltration rate during the steady rain is equal to rainfall intensity if the top layer has enough storage to absorb infiltrated water for a given event, $K_{pseudo}$ can be calculated by Green-Ampt equation.

$$f = I = K_{pseudo} \times \frac{\psi_f + Z_{threshold}}{Z_{threshold}} \tag{30}$$

Rearranging equation (30) yields,

$$K_{pseudo} = I \times \frac{Z_{threshold}}{\psi_f + Z_{threshold}} \tag{31}$$

Once $K_{pseudo}$ is calculated, boundary conditions for Case 2 can be set as below.

$$Z_{top} = Z_{threshold} \qquad \dashrightarrow \qquad K_{eff} = K_{pseudo} \tag{32}$$

$$Z_{top} = 0 \qquad \dashrightarrow \qquad K_{eff} = K_{bottom} \tag{33}$$

Again, using two boundary conditions, a linear equation with $K_{eff}$ can be written as below and equation (34) also has the information about both rainfall characteristic and the depth of layered soils.

$$K_{eff} = \frac{K_{pseudo} - K_{bottom}}{Z_{threshold}} \times Z_{top} + K_{bottom} \tag{34}$$

- Case 3: $I < K_{s\_bottom} < K_{s\_top}$

In this case, there is no need to estimate $K_{eff}$ since all rainfall on surface will infiltrate into the soil and surface runoff will not be generated if the depth of two layers is deep enough to store the water, otherwise, saturation excess runoff generation will only occur.

- Unsteady rain

Under the unsteady rain, rainfall intensity is changed over time so that surface ponding should be considered to determine $K_{eff}$ of two-layered soils. Under Yen-Chow hyetograph, equation (25) can be used to determine whether surface ponding occurs for a given storm.

If the surface ponding occurs during a given storm, equation (29) will be used for a $K_{eff}$, otherwise, all rainfall will infiltrate into the soil if both layers have enough storage, so that there is no need to estimate effective Green-Ampt parameters for two layers.

# CHAPTER 4. RESULTS AND DISCUSSION

## 4.1. STEADY RAIN

### 4.1.1. Estimation of $Z_{threshold}$

Simple procedures to estimate $Z_{threshold}$ were discussed in Chapter 3. To test whether the approximation of $Z_{threshold}$ is valid or not, four different steady storm events are simulated with simulate MIKE SHE based on Richards equation with two-layered soils with different depths of top layer, hereafter, called numerical solution. Four different steady storm events are listed in Table 4.1.

**TABLE 4.1 STEADY STORM EVENTS**

| **Event** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| $I$ [mm/hr] | 30 | 15 | 7.5 | 3.75 |
| Duration [hr] | 5 | 10 | 20 | 40 |

Event 1 and 2 are the case where rainfall intensity ($I$) is greater than $K_s$ of top layer, and Event 3 and 4 are the case where rainfall intensity is less than $K_s$ of top layer. Numerical solution was examined to determine the maximum saturated depth for each event and the results were compared with the calculated $Z_{threshold}$. Cumulative depth of runoff ($Q$) and subsurface storage ($S$) are obtained from each event. The numerical solution results are shown in Table 4.2 and Figure 4.1. In Table 4.2, $Q$ and $S$ are measured only on the pervious area of the model domain and Figure 4.1 represents the cumulative infiltration water ($S$) for the storm events with different thicknesses of the top layer.

**TABLE 4.2 NUMERICAL SOLUTION RESULTS WITH DIFFERENT DEPTHS OF TOP LAYER**

| Top layer thickness *Z* [m] | Event 1 | | Event 2 | | Event 3 | | Event 4 | |
|---|---|---|---|---|---|---|---|---|
| | ***Q*** **[mm]** | ***S*** **[mm]** | ***Q*** **[mm]** | ***S*** **[mm]** | ***Q*** **[mm]** | ***S*** **[mm]** | ***Q*** **[mm]** | ***S*** **[mm]** |
| 0.1 | 99.45 | 50.43 | 86.79 | 63.10 | 68.12 | 81.75 | 37.43 | 112.43 |
| 0.2 | 81.71 | 68.10 | 65.13 | 84.51 | 46.46 | 103.13 | 22.07 | 127.50 |
| 0.3 | 76.94 | 73.01 | 47.42 | 102.00 | 27.93 | 121.30 | 10.00 | 139.19 |
| 0.4 | 76.94 | 73.01 | 35.86 | 113.53 | 11.81 | 137.18 | 1.12 | 148.17 |
| 0.5 | 76.94 | 73.01 | 35.48 | 114.32 | 0.49 | 148.47 | 0.00 | 149.19 |
| 0.6 | 76.94 | 73.01 | 35.48 | 114.32 | 0.00 | 150.01 | 0.00 | 150.00 |
| 0.7 | 76.94 | 73.01 | 35.48 | 114.32 | 0.00 | 150.01 | 0.00 | 150.00 |

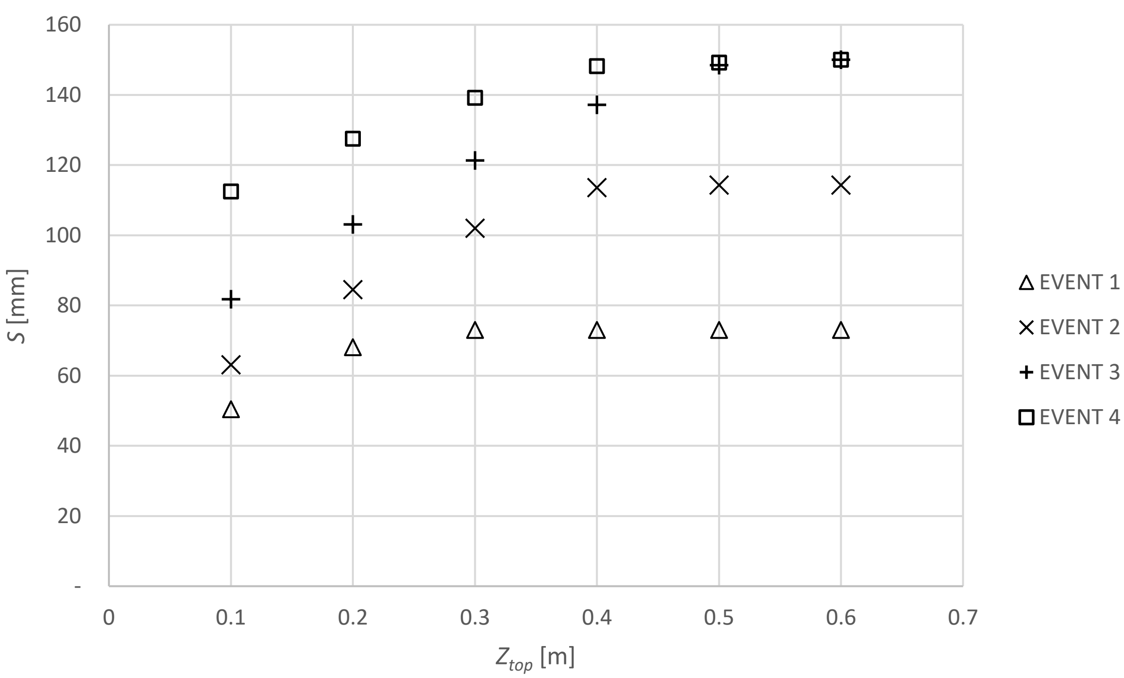


**FIGURE 4.1 TOTAL SUBSURFACE STORAGE (*S*) WITH DIFFERENT DEPTHS OF TOP LAYER BASED ON NUMERICAL SOLUTION**

Based on numerical solution, as the depth of top layer increase, the cumulative subsurface storage (*S*) increases because of coarse-over-fine stratifications. However, at some point, *S* is going to be constant even though the depth of top layer increase. For example, in the case of event 1, *S* is going to be constant when depth of top layer is greater than 0.3m so that we can infer $Z_{threshold}$ of event 1 is in between 0.2 and 0.3m. This inference can be compared to the value calculated with equation (26). Table 4.3 is the comparison between the ranges of depth of $Z_{threshold}$ inferred from MIKE SHE numerical solution and values of $Z_{threshold}$ calculated using equation (26). Initial moisture content ($\theta_i$) of the top layer is equal to field capacity ($\theta_{fc} = 0.16$) in both simulations and thus initial moisture deficit of the top layer is equal to 0.27. The results show that all values of $Z_{threshold}$ using equation (26) lie within the range of *Z* inferred from MIKE SHE numerical solution.

**TABLE 4.3 COMPARISON $Z_{threshold}$ BETWEEN NUMERICAL SOLUTION AND SIMPLE PROCEDURES**

| Storm Event | MIKE SHE | Estimation of $Z_{threshold}$ | |
|---|---|---|---|
| | Range of *Z* [m] | *F* [mm] | $Z_{threshold}$ [m] |
| 1 | 0.2 - 0.3 | 71.62 | 0.27 |
| 2 | 0.4 - 0.5 | 121.31 | 0.45 |
| 3 | 0.5 - 0.6 | 150 | 0.56 |
| 4 | 0.5 - 0.6 | 150 | 0.56 |

Figure 4.2 represents the infiltration rate by numerical solution at specific location (*X* = 305m, *Y* = 400m) of V-Shaped catchment for the case that depth of top layer is greater than $Z_{threshold}$ of each event (i.e. the top layer has enough storage to absorb infiltrated water for a given storm). When $K_s$ of the top layer is greater than *I* such as event 3 and 4, infiltration rate is equal to rainfall intensity until the end of the events and thus all water

on the ground surface will infiltrate into the soil. However, when $K_s$ of the top layer is less than rainfall intensity such as event 1 and 2, infiltration process is more complicated and difficult to predict. However, using equation (19), which is a modified explicit function of Green-Ampt method for estimating cumulative infiltration water, shows good agreement with MIKE SHE numerical solution to estimate $Z_{threshold}$ for a given storm as shown in Table 4.3.

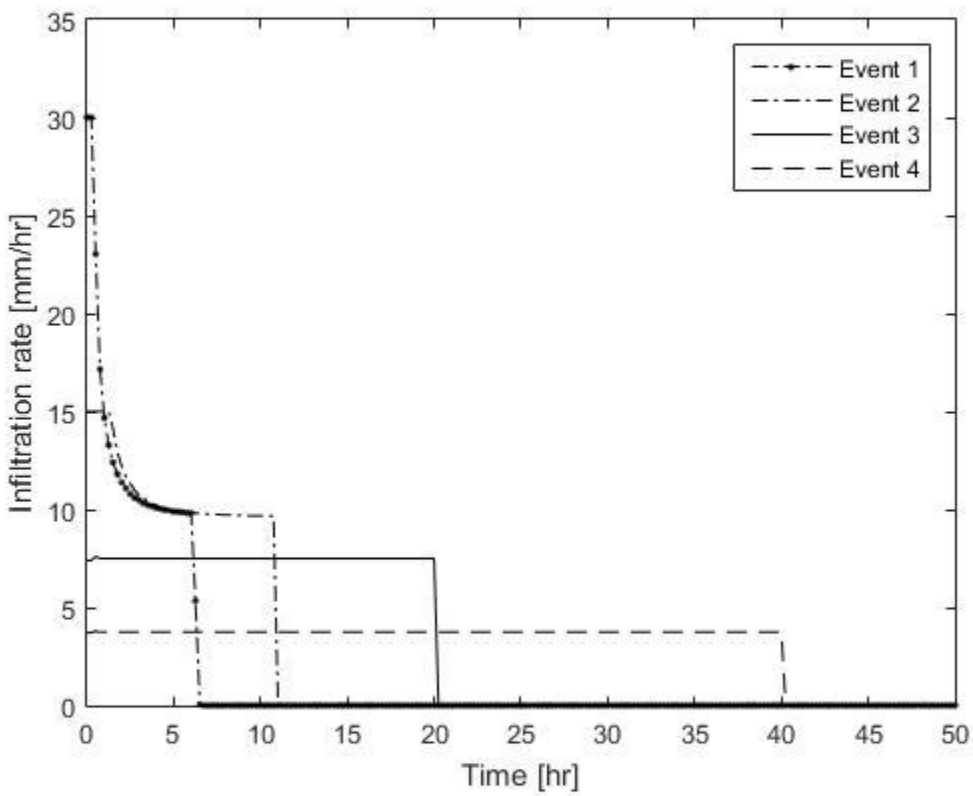


**FIGURE 4.2 INFILTRATION RATE AT *X* = 305M, *Y* = 400M BY NUMERICAL SOLUTION (DEPTH OF TOP LAYER > $Z_{threshold}$)**

To validate the estimation of $Z_{threshold}$, three more constant storm events were simulated, each of which has 300mm of rainfall depth with different rainfall intensity and duration. Before the simulation, $Z_{threshold}$ was estimated using equation (26) and the results compared to numerical solution.

Table 4.4 shows the constant storm events, the estimation of $Z_{threshold}$ of each event and the ranges of $Z_{threshold}$ by numerical solution. Table 4.5 and Figure 4.3 represent the results of numerical solution for each event. Based on numerical solution, all simple approximations of $Z_{threshold}$ lie in between the range of $Z_{threshold}$ depth based on numerical solution. Therefore, these comparisons show that estimation of $Z_{threshold}$ presented here is a good approximation to decide maximum saturated depth under steady rain.

**TABLE 4.4 CONSTANT RAINFALL EVENTS AND ESTIMATION OF $Z_{threshold}$**

| Event | *I* [mm/hr] | Duration [hr] | Estimation of $Z_{threshold}$ | | Range of *Z* (MIKE SHE) |
|---|---|---|---|---|---|
| | | | *F* [mm] | $Z_{threshold}$ [m] | |
| 5 | 30 | 10 | 125.93 | 0.47 | 0.4-0.5 |
| 6 | 15 | 20 | 224.27 | 0.83 | 0.8-0.9 |
| 7 | 7.5 | 40 | 300 | 1.11 | 1.1-1.2 |

**TABLE 4.5 SIMULATION RESULTS OF EVENT 5,6 AND 7 BASED ON NUMERICAL SOLUTION**

| Event 5 | | | Event 6 | | | Event 7 | | |
|---|---|---|---|---|---|---|---|---|
| Top layer thickness *Z* [m] | *Q* [mm] | *S* [mm] | Top layer thickness *Z* [m] | *Q* [mm] | *S* [mm] | Top layer thickness *Z* [m] | *Q* [mm] | *S* [mm] |
| 0.4 | 180.85 | 118.37 | 0.7 | 95.88 | 202.33 | 1 | 0.74 | 294.18 |
| 0.5 | 178.24 | 121.58 | 0.8 | 89.76 | 209.48 | 1.1 | 0.00 | 297.16 |
| 0.6 | 178.24 | 121.58 | 0.9 | 89.76 | 210.03 | 1.2 | 0.00 | 300.03 |
| 0.7 | 178.24 | 121.58 | 1.0 | 89.76 | 210.03 | 1.3 | 0.00 | 300.03 |

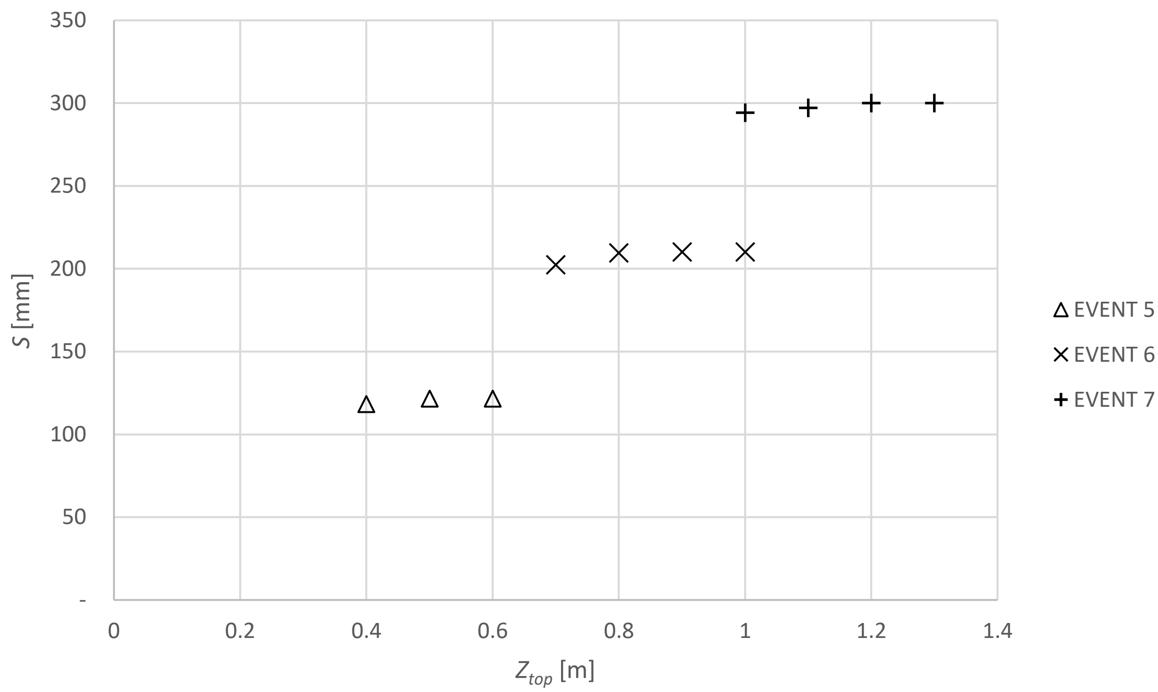


**FIGURE 4.3 SIMULATION RESULTS OF EVENT 5,6 AND 7 BASED ON NUMERICAL SOLUTION**

Since the modified explicit function of Green-Ampt method was used for accumulated infiltration(*F*) as discussed in Chapter 3, instead of using an original explicit function proposed by Mailapalli et al. (2009), it is worth comparing the results between the original and the modified explicit function of Green-Ampt method. Since the modified explicit function is only used when rainfall intensity is greater than $K_s$ of the top layer, the storm events 1, 2, 5 and 6 are selected for this comparison. Those results also will be compared to numerical solution. The cumulative infiltration water (*F*) based on numerical solution, an original explicit function and a modified explicit function are listed in Table 4.6.

**TABLE 4.6 COMPARISON CUMULATIVE INFILTRATED WATER (*F*) BETWEEN ORIGINAL AND MODIFIED EXPLICIT FUNCTION UNDER STEADY RAIN**

| Event | *I* [mm/hr] | *t* [hr] | *F*_Numerical solution [mm] | *F*_Original Explicit [mm] | Error (%) | *F*_Modified Explicit [mm] | Error (%) |
|---|---|---|---|---|---|---|---|
| 1 | 30 | 5 | 73.01 | 72.63 | -0.52 | 71.62 | -1.91 |
| 2 | 15 | 10 | 114.32 | 126.88 | 10.99 | 121.31 | 6.11 |
| 5 | 30 | 10 | 121.58 | 126.88 | 4.36 | 125.93 | 3.58 |
| 6 | 15 | 20 | 210.03 | 229.59 | 9.31 | 224.27 | 6.78 |

Although there are some discrepancies, the errors of a modified explicit function are less than those of an original method except for the event 1 that both errors are negligibly small.

Figure 4.4 shows the infiltration rate of four storm events by the modified explicit function of Green-Ampt (red line) and numerical solution (blue dotted line) where the case that the depth of the top layer is greater than $Z_{threshold}$. After some period, all events show that the infiltration rate by Green-Ampt method is slightly greater than the rate by Richards equation. Since the modified Green-Ampt infiltration rate tends to slightly overestimate *f*, when this is used to determine $Z_{threshold}$, the result is also a slight overestimation of $Z_{threshold}$. However, as shown in Table 4.3 and Table 4.4, calculated $Z_{threshold}$ falls within layer range based on MIKE SHE numerical simulations. Furthermore, overestimating $Z_{threshold}$ is conservative, from an engineering design perspective, since overestimating will require application of the equation (29) more conservatively.

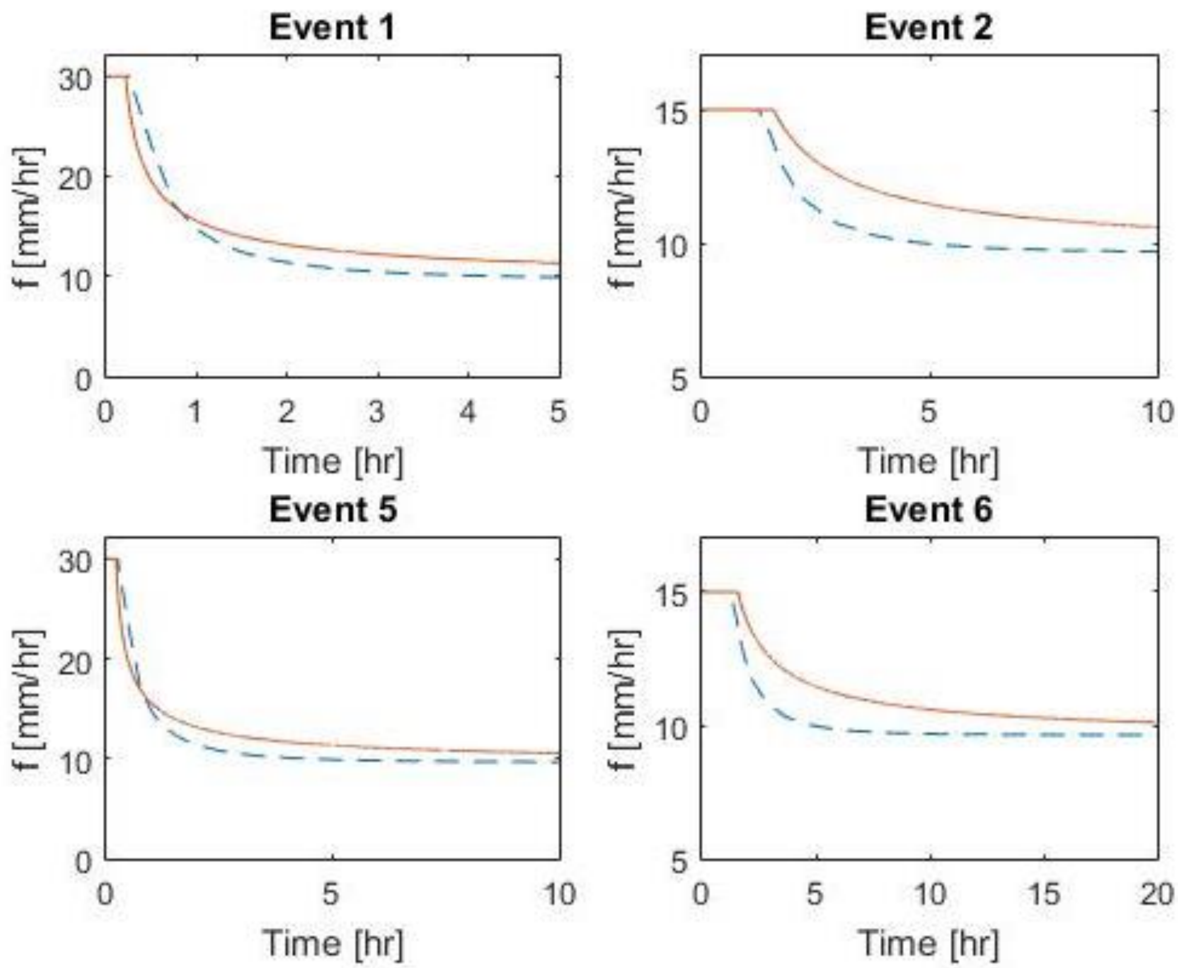


**FIGURE 4.4 COMPARISON INFILTRATION RATE BETWEEN MODIFIED EXPLICIT FUNCTION OF GREEN-AMPT METHOD (RED LINE) AND NUMERICAL SOLUTION (BLUE DOTTED LINE)**

### 4.1.2. Simulation Results with Effective Green-Ampt Parameters

After the values of $Z_{threshold}$ for each event were estimated, $K_{eff}$ for a homogeneous soil that approximates the behavior of the two-layered soils was calculated by using either equation (29) or (34). Under steady rain, there are three possible cases in terms of rainfall intensity and each case will be examined.

(1) Case 1 : $I > K_{s\_top}$

Calculated values of $K_{eff}$ of storm event 1 with the different depths of top layer are listed in Table 4.7. Because $Z_{threshold}$ of event 1 is 0.27m, the range of thicknesses of the top layer considered to calculate $K_{eff}$ is between 0 and 0.27m. When the depth of the top layer is equal to zero, $K_{eff}$ should be $K_s$ of the bottom layer and when the depth of the top layer is equal to $Z_{threshold}$, $K_{eff}$ should be $K_s$ of the top layer. The calculated values of $K_{eff}$ in between those values can be obtained by equation (29).

**TABLE 4.7 $K_{eff}$ OF STORM EVENT 1 WITH DIFFERENT DEPTHS OF TOP LAYER**

| **Depth of top layer [m]** | 0 | 0.1 | 0.2 | 0.27 (= $Z_{threshold}$) |
|---|---|---|---|---|
| **$K_{eff}$ [mm/hr]** | 1.91 | 4.73 | 7.55 | 9.53 |

After estimating $K_{eff}$ with different depth of the top layer, MIKE SHE simulation based on Green-Ampt with effective soil parameters is simulated and these results are compared with numerical solution. Figure 4.5 shows the cumulative subsurface storage (*F*) for an event 1 for the two different depths of the top layer. The red line represents *F* based on numerical solution and the blue dotted line represents *F* based on Green-Ampt method using effective soil parameters. There is an inflection point in the simulation results based on numerical solution based on Richards equation due to the different soil characteristics of two layers. Nevertheless, the difference between the cumulative infiltrated water by two methods is negligible at the end of the storm in both cases. The errors of two different depths of the top layer, which are 0.1m and 0.2m, are 1.45% and 2.19%, respectively. Figure 4.6 represents infiltration rate (*f*) of two cases and there are some discrepancies between Richards equation and Green-Ampt method using effective soil parameters. However, in terms of accumulative infiltration, the results based on Green-Ampt method using effective soil parameters show good agreement compared to the simulation results based on Richards equation.

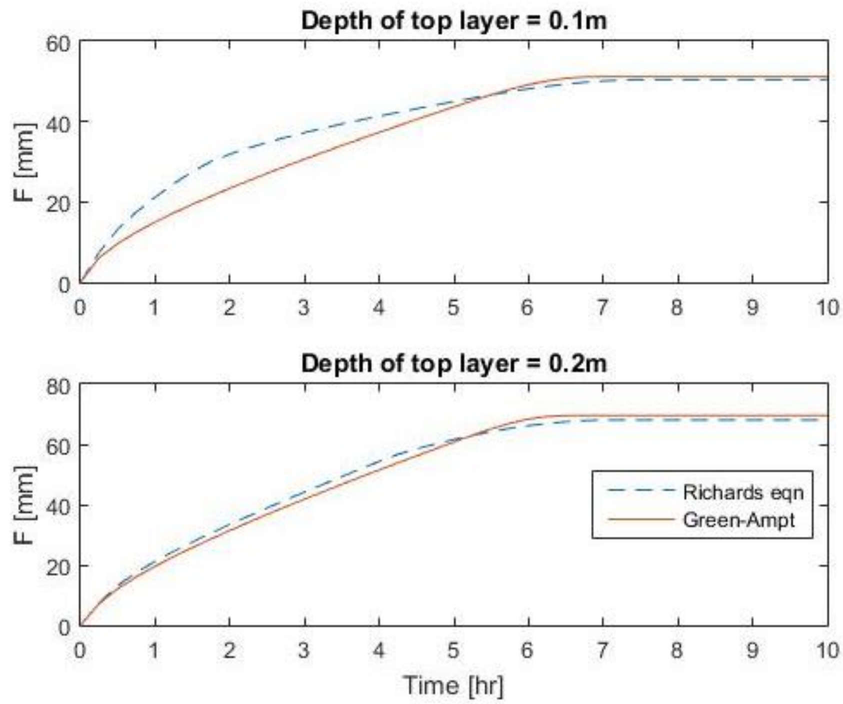


**FIGURE 4.5 CUMULATIVE SUBSURFACE STORAGE UNDER STORM EVENT 1 WITH DIFFERENT DEPTHS OF TOP LAYER**

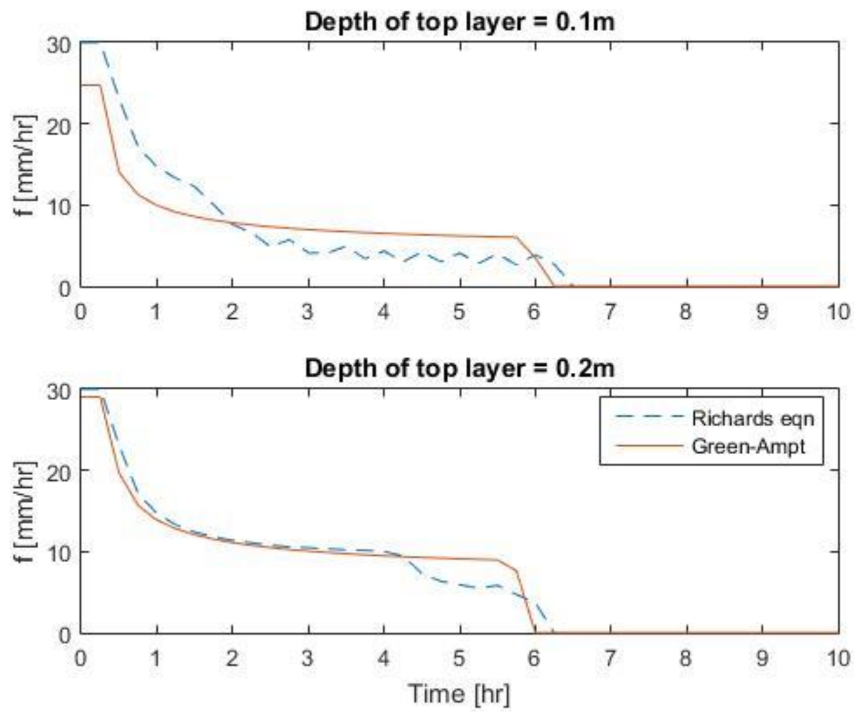


**FIGURE 4.6 INFILTRATION RATE UNDER STORM EVENT 1 WITH DIFFERENT DEPTHS OF TOP LAYER**

Storm event 2 is also the case where rainfall intensity is greater than $K_s$ of the top layer. Thus, $K_{eff}$ for different depths of the top layer can be obtained by equation (29) as well. The values of $K_{eff}$ for different depths of the top layer and the simulation results are listed in Table 4.8. The percentage errors ranged from 0.44 to 3.71% assuming the simulation results based on numerical solution are true.

**TABLE 4.8 CUMULATIVE SUBSURFACE STORAGE BY RICHARDS EQUATION AND GREEN -AMPT FOR EVENT 2**

| $Z_{top}$ [m] | $K_{eff}$ [mm/hr] | Cumulative $F$ by Richards eqn. [mm] | Cumulative $F$ based on Green-Ampt [mm] | Error [%] |
|---|---|---|---|---|
| 0 | 1.91 | - | - | - |
| 0.1 | 3.60 | 63.10 | 64.23 | 1.79 |
| 0.2 | 5.30 | 84.51 | 83.77 | -0.88 |
| 0.3 | 6.99 | 102.00 | 101.55 | -0.44 |
| 0.4 | 8.68 | 113.53 | 117.74 | 3.71 |
| 0.45 (=$Z_{threshold}$) | 9.53 | - | - | - |

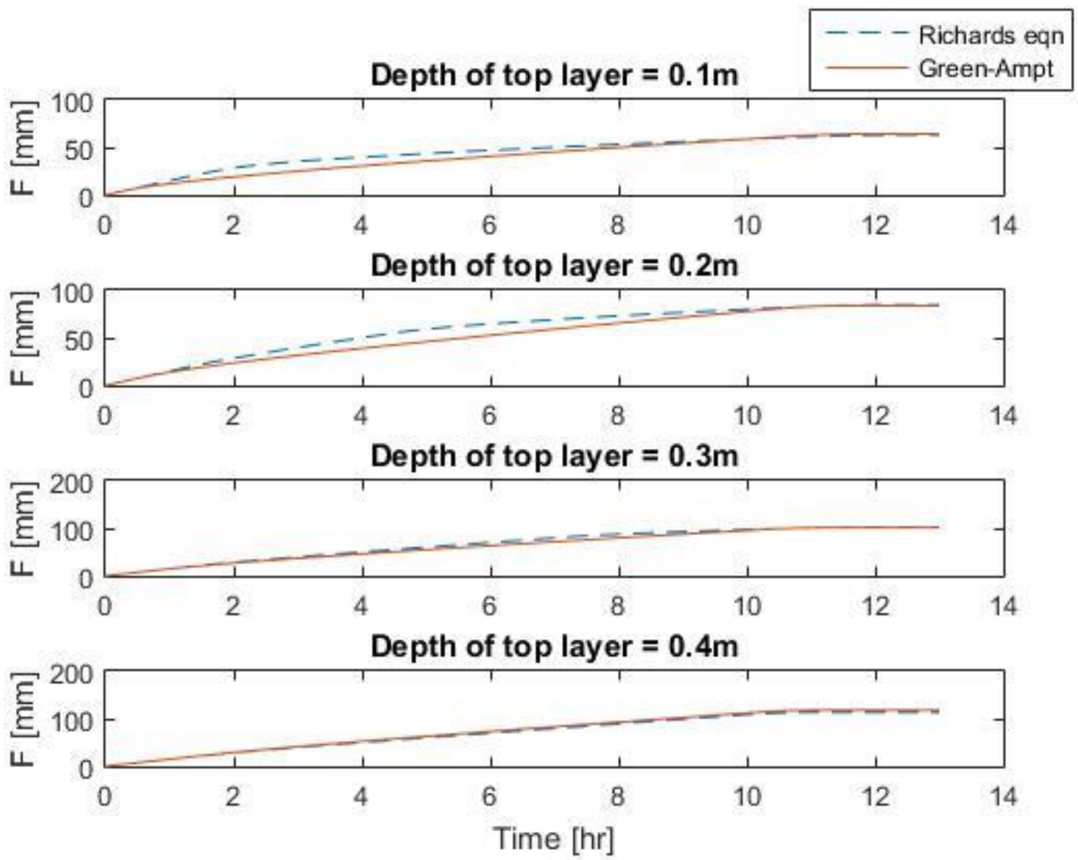


**FIGURE 4.7 CUMULATIVE SUBSURFACE STORAGE FOR STORM EVENT 2**

(2) Case 2 : $K_{s\_bottom} < I < K_{s\_top}$

In this case, $K_{pseudo}$ should be calculated in advance by using equation (30) in order to estimate $K_{eff}$. For event 3, $K_{pseudo}$ is equal to 6.77mm/hr. Also, calculated $Z_{threshold}$ was 0.56m so that the range of depth of the top layer to be considered is in between 0 and 0.56m. In case 2, $K_{eff}$ for different depths of the top layer can be calculated by using equation (34) with the value of $K_{pseudo}$. Numerical solution and MIKE SHE simulation based on Green-Ampt method using effective soil parameters are shown in the Table 4.9 and Figure 4.8, and those results show that there are no significant differences between two simulation results.

**TABLE 4.9 CUMULATIVE SUBSURFACE STORAGE BY RICHARDS EQUATION AND GREEN -AMPT FOR EVENT 3**

| $Z_{top}$ [m] | $K_{eff}$ [mm/hr] | Cumulative $F$ by Richards eqn. [mm] | Cumulative $F$ based on Green-Ampt [mm] | Error [%] |
|---|---|---|---|---|
| 0 | 1.91 | - | - | - |
| 0.1 | 2.78 | 81.75 | 84.20 | 3.00 |
| 0.2 | 3.65 | 103.13 | 102.44 | -0.67 |
| 0.3 | 4.52 | 121.30 | 118.39 | -2.40 |
| 0.4 | 5.38 | 137.18 | 131.12 | -4.42 |
| 0.5 | 6.25 | 148.47 | 143.58 | -3.29 |
| 0.56 (= $Z_{threshold}$) | 6.77 | - | - | - |

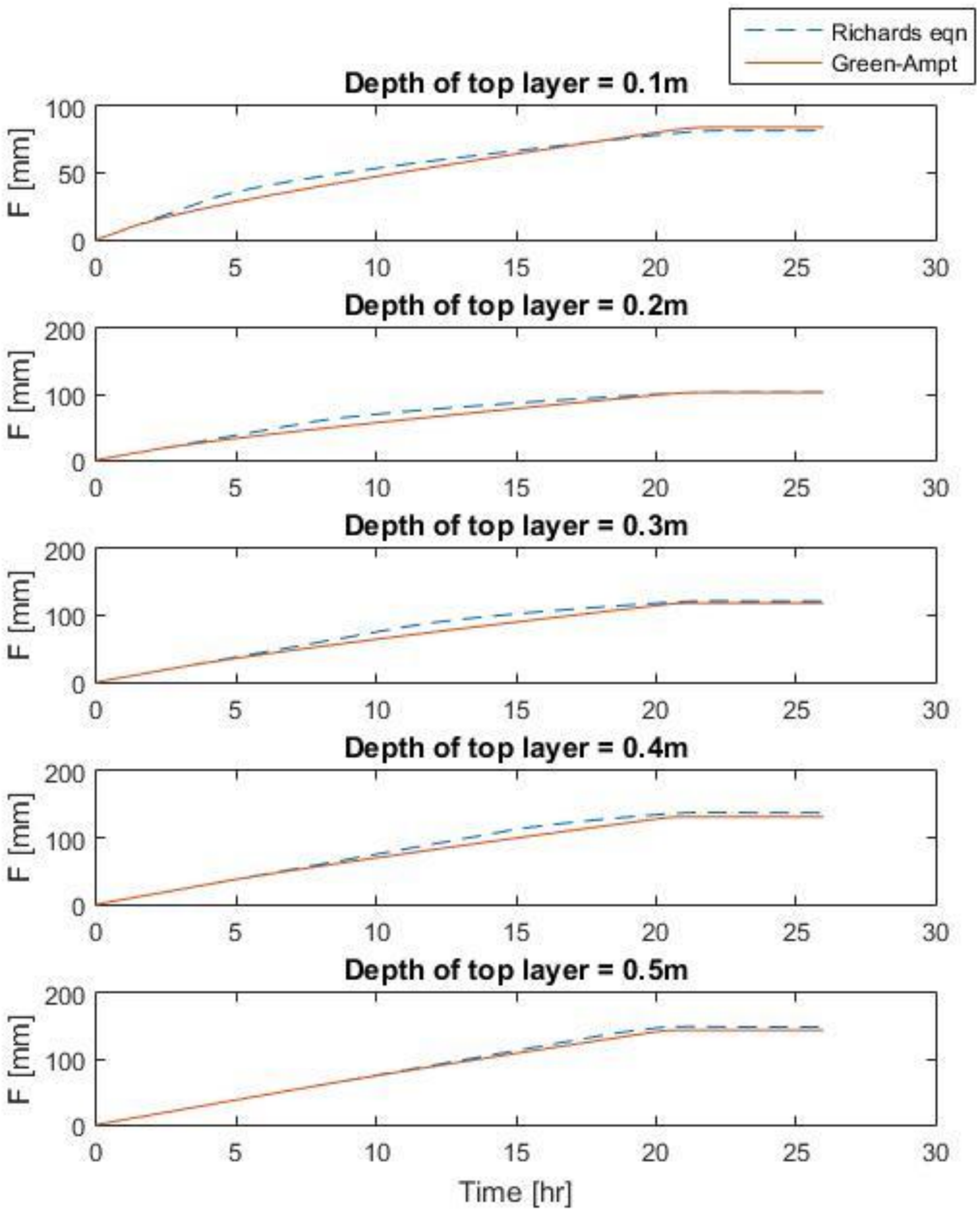


**FIGURE 4.8 CUMULATIVE SUBSURFACE STORAGE FOR STORM EVENT 3**

Storm event 4, which has less rainfall intensity but longer storm duration compared to event 3, is also considered, and the same procedure is applied as the procedure of event 3. Even though $Z_{threshold}$ is the same as event 3, $K_{pseudo}$ of event 4 is 3.39mm/hr because of the lower rainfall intensity and thus the values of $K_{eff}$ for different depths of the top layer are different. Table 4.10 and Figure 4.9 show MIKE SHE simulation results based on numerical solution and Green-Ampt method using effective soil parameters. The results show good agreement compared to the simulation results based on Richards equation with two-layered soils.

**TABLE 4.10 CUMULATIVE SUBSURFACE STORAGE BY RICHARDS EQUATION AND GREEN -AMPT FOR EVENT 4**

| $Z_{top}$ [m] | $K_{eff}$ [mm/hr] | Cumulative $F$ by Richards eqn. [mm] | Cumulative $F$ based on Green-Ampt [mm] | Error [%] |
|---|---|---|---|---|
| 0 | 1.91 | - | - | - |
| 0.1 | 2.17 | 112.43 | 113.77 | 1.19 |
| 0.2 | 2.44 | 127.50 | 123.45 | -3.18 |
| 0.3 | 2.70 | 139.19 | 132.08 | -5.11 |
| 0.4 | 2.97 | 148.17 | 138.54 | -6.50 |
| 0.5 | 3.23 | 149.19 | 145.21 | -2.67 |
| 0.56 (=$Z_{threshold}$) | 3.39 | - | - | - |

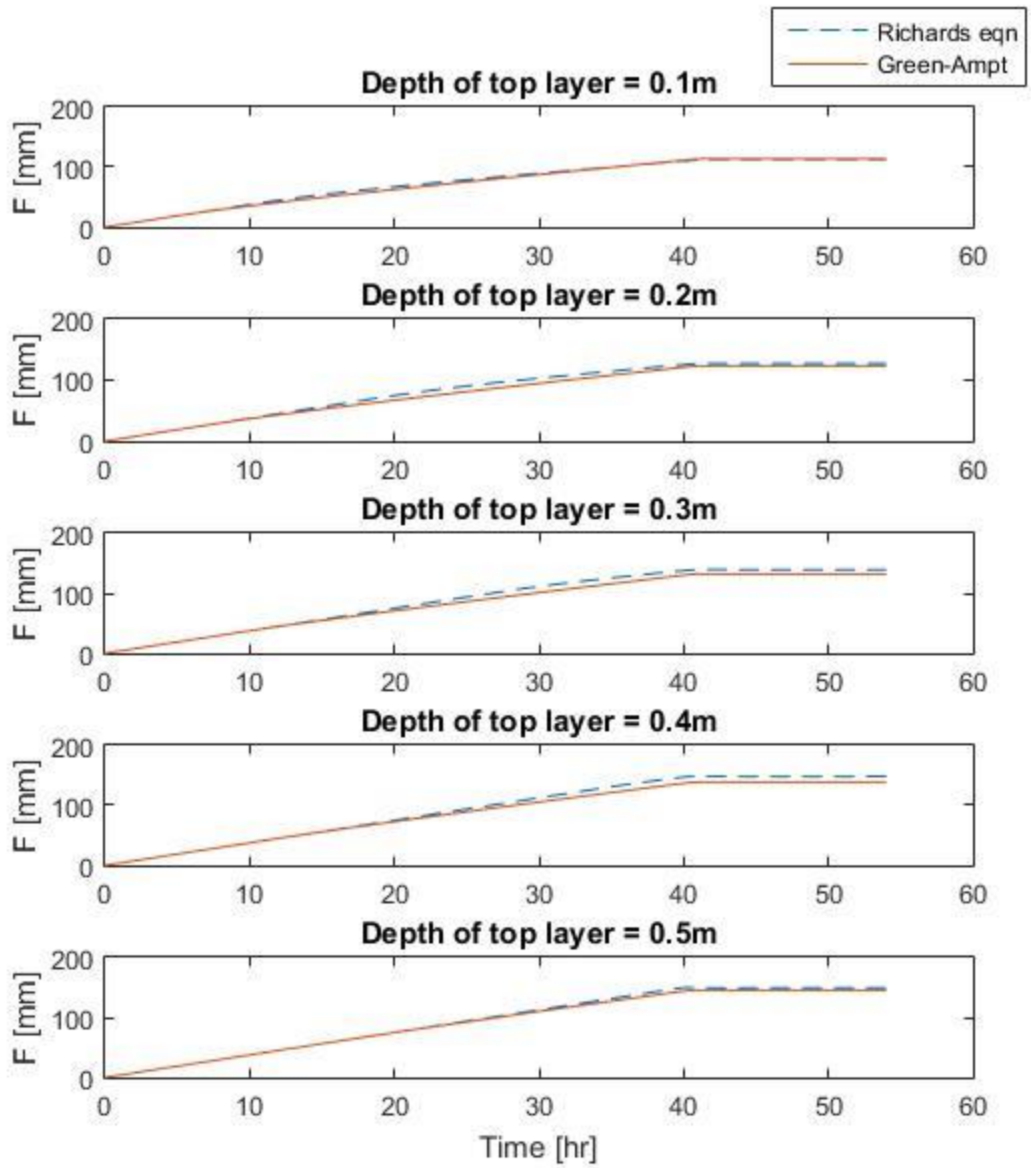


**FIGURE 4.9 CUMULATIVE SUBSURFACE STORAGE UNDER STORM EVENT 4**

In conclusion, the accumulated infiltration ($F$) under four different steady rain events are compared with numerical solution based on Richards equation with two-layered soils to verify a simple procedure of estimating effective Green-Ampt soil parameters for two-layered soils introduced in this thesis. The comparisons show that the differences are negligible with respect to the cumulative infiltration water. The maximum error between two simulations is -6.5% which is reasonably acceptable considering many other uncertainties of infiltration practice.

## 4.2. UNSTEADY RAIN

### 4.2.1. Yen-Chow Hyetograph

As discussed earlier, Yen-Chow hyetograph (Yen & Chow, 1980) was used for the rainfall distribution of unsteady rain. Eight different storm events are examined to consider wide ranges of rainfall intensity and storm duration. Table 4.11 and Figure 4.10 show eight different Yen-Chow hyetographs and in Figure 4.10, the blue lines represent rainfall distribution over time and the red straight lines represent $K_s$ of the top layer.

**TABLE 4.11 EIGHT DIFFERENT YEN-CHOW HYETOGRAPHS**

| **Event ID** | $P$ **[mm]** | $t_d$ **[hr]** | $I_k$ **[mm/hr]** | $t_k$ **[hr]** |
|---|---|---|---|---|
| YC1 | 150 | 5 | 60 | 1.875 |
| YC2 | 150 | 10 | 30 | 3.75 |
| YC3 | 150 | 15 | 20 | 5.625 |
| YC4 | 150 | 20 | 15 | 7.5 |
| YC5 | 50 | 10 | 10 | 3.75 |
| YC6 | 100 | 10 | 20 | 3.75 |
| YC7 | 200 | 10 | 40 | 3.75 |
| YC8 | 300 | 10 | 60 | 3.75 |

Note that P is total depth of rain, $t_d$ is total duration of the storm, $I_k$ is the peak intensity and $t_k$ is the time at peak.

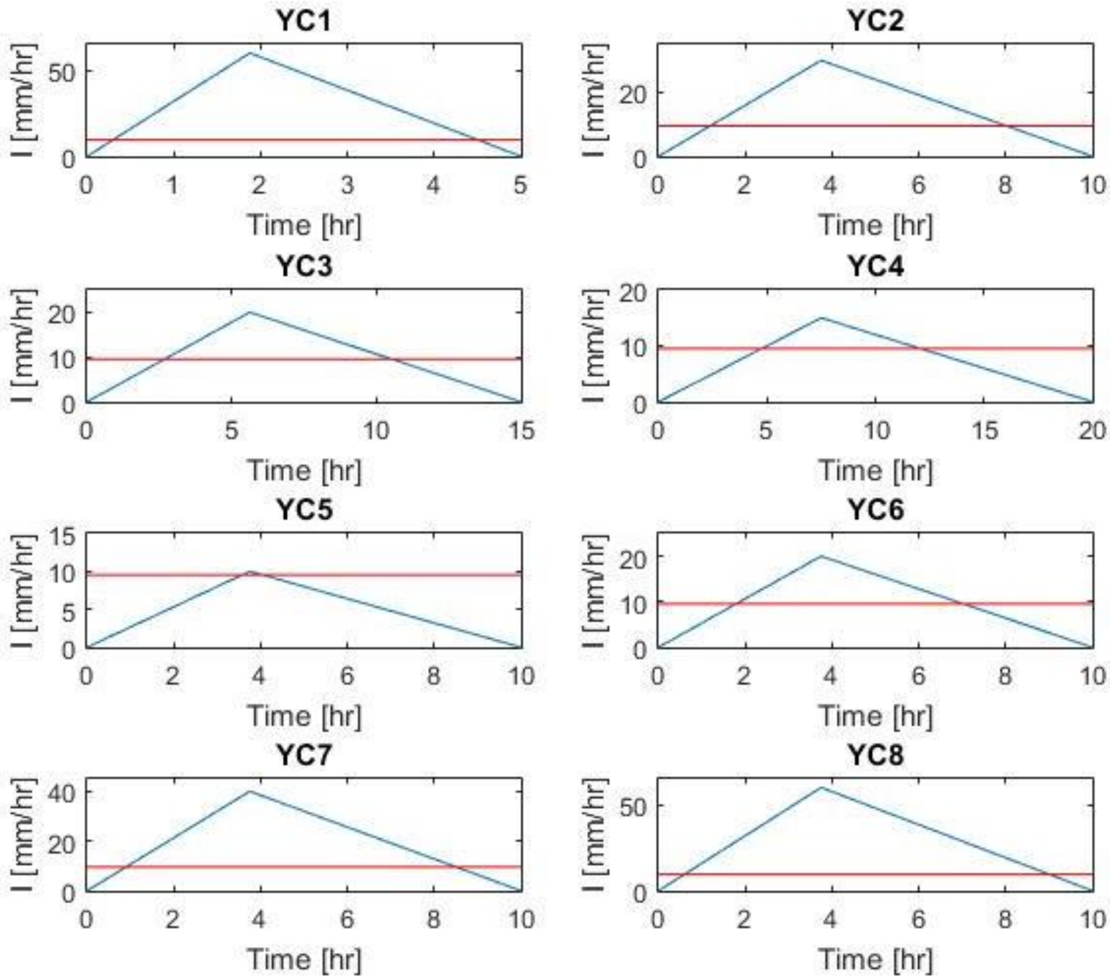


**FIGURE 4.10 EIGHT DIFFERENT YEN-CHOW HYETOGRAPHS FOR UNSTEADY RAIN EVENTS**

### 4.2.2. Estimation of $Z_{threshold}$

Accumulated infiltration (*F*) for eight different Yen-Chow hyetographs are estimated to calculate $Z_{threshold}$. Table 4.12 show estimated *F* based on the procedures introduced in Table 3.4 and those values were compared to the MIKE SHE simulation results based on Richards equation with enough depth of the top layer that the bottom layer does not affect the infiltration. Surface ponding occurs for all the events except for YC5. The error between accumulated infiltration based on Richards equation ($F$_Richards) and accumulated infiltration based on the modified explicit function of Green-Ampt method (F_Modified Explicit) for all events were reasonable, with the Green-Ampt-based method overestimating accumulated infiltration by 0.0 to 7.6%. Also, $Z_{threshold}$ was calculated based on equation (26) with the same initial moisture deficit as discussed in Chapter 3.2 and thus the initial moisture deficit of top layer is equal to 0.27.

**TABLE 4.12 ESTIMATED ACCUMULATED INFILTRATION AND $Z_{threshold}$**

| Event ID | $F$_Richards [mm] | $F$_Modified Explicit [mm] | Error (%) | $Z_{threshold}$ [mm] |
|---|---|---|---|---|
| YC1 | 62.54 | 63.25 | 1.14 | 0.23 |
| YC2 | 92.84 | 99.68 | 7.37 | 0.37 |
| YC3 | 117.33 | 125.92 | 7.33 | 0.47 |
| YC4 | 135.46 | 143.23 | 5.74 | 0.53 |
| YC5 | 50.00 | 50 | 0.01 | 0.19 |
| YC6 | 82.62 | 87.82 | 6.29 | 0.33 |
| YC7 | 98.22 | 105.67 | 7.58 | 0.39 |
| YC8 | 104.12 | 111.84 | 7.41 | 0.41 |

4.2.3. Simulation Results with Effective Green-Ampt Parameters

To estimate infiltration process into two-layered soils, the ranges of thicknesses of top layer considered are in between 0 and calculated $Z_{threshold}$ for each storm event and the interval of the thickness of top layer to be simulated is 0.1m. For example, since calculated $Z_{threshold}$ was 0.23 for YC1, the thicknesses of top layer to be considered is 0.1 and 0.2m. The values of $K_{eff}$ for different depth of top layer are calculated by equation (29). The results of MIKE SHE simulation based on Green-Ampt method using effective soil parameters of the two layers are compared to the results based on numerical solution and the comparisons of cumulative infiltrated water for eight Yen-Chow storm events are shown in Table 4.13. Note that in Table 4.13, Cumul. *F1* is cumulative subsurface storage based on Richards equation with two-layered soils and Cumul. *F2* is cumulative subsurface storage based on Green-Ampt method using effective soil properties of the two layers. The depth of infiltrated water for each storm event was measured only in pervious area in the model domain.

**TABLE 4.13 COMPARISONS ACCUMULATED INFILTRATION FOR EIGHT DIFFERENT YEN-CHOW STORM EVENTS**

| Event ID | $Z_{top}$ [m] | $K_{eff}$ [mm/hr] | Cumul. *F1* [mm] | Cumul. *F2* [mm] | Error (%) |
|---|---|---|---|---|---|
| YC1 | 0 | 1.91 | - | - | - |
| | 0.1 | 5.16 | 47.14 | 47.01 | -0.28 |
| | 0.2 | 8.41 | 61.63 | 63.48 | 3.01 |
| | 0.23 | 9.53 | - | - | - |
| YC2 | 0 | 1.91 | - | - | - |
| | 0.1 | 3.97 | 58.05 | 58.87 | 1.40 |
| | 0.2 | 6.04 | 78.09 | 76.74 | -1.72 |
| | 0.3 | 8.10 | 91.53 | 92.37 | 0.91 |
| | 0.37 | 9.53 | - | - | - |
| YC3 | 0 | 1.91 | - | - | - |
| | 0.1 | 3.54 | 66.71 | 69.94 | 4.83 |
| | 0.2 | 5.18 | 88.53 | 89.07 | 0.61 |
| | 0.3 | 6.81 | 106.54 | 106.25 | -0.28 |
| | 0.4 | 8.44 | 117.17 | 120.07 | 2.47 |
| | 0.47 | 9.53 | - | - | - |

**TABLE 4.14 COMPARISONS ACCUMULATED INFILTRATION FOR EIGHT DIFFERENT YEN-CHOW STORM EVENTS (CONTINUED)**

| Event ID | $Z_{top}$ [m] | $K_{eff}$ [mm/hr] | Cumul. *F1* [mm] | Cumul. *F2* [mm] | Error (%) |
|---|---|---|---|---|---|
| YC4 | 0 | 1.91 | - | - | - |
| | 0.1 | 3.35 | 74.11 | 80.59 | 8.75 |
| | 0.2 | 4.78 | 96.98 | 100.85 | 3.98 |
| | 0.3 | 6.22 | 116.49 | 117.61 | 0.96 |
| | 0.4 | 7.65 | 133.06 | 131.17 | -1.42 |
| | 0.5 | 9.09 | 135.46 | 141.57 | 4.51 |
| | 0.53 | 9.53 | - | - | - |
| YC5 | 0 | 1.91 | - | - | - |
| | 0.1 | 6.02 | 48.62 | 50.00 | 2.84 |
| | 0.19 | 9.53 | - | - | - |
| YC6 | 0 | 1.91 | - | - | - |
| | 0.1 | 4.25 | 55.77 | 57.84 | 3.72 |
| | 0.2 | 6.59 | 74.99 | 74.52 | -0.63 |
| | 0.3 | 8.94 | 82.62 | 87.93 | 6.43 |
| | 0.33 | 9.53 | - | - | - |
| YC7 | 0 | 1.91 | - | - | - |
| | 0.1 | 3.86 | 59.23 | 59.47 | 0.41 |
| | 0.2 | 5.80 | 79.68 | 77.82 | -2.34 |
| | 0.3 | 7.75 | 94.99 | 95.11 | 0.12 |
| | 0.39 | 9.53 | - | - | - |
| YC8 | 0 | 1.91 | - | - | - |
| | 0.1 | 3.75 | 60.52 | 60.17 | -0.58 |
| | 0.2 | 5.59 | 81.37 | 79.12 | -2.76 |
| | 0.3 | 7.43 | 97.72 | 96.97 | -0.77 |
| | 0.4 | 9.27 | 104.12 | 112.26 | 7.83 |
| | 0.41 | 9.53 | - | - | - |

The cumulative infiltrated water from MIKE SHE simulations based on Green-Ampt method using effective soil properties show good agreement compared to the simulation results based on Richards equation with two-layered soils. The percentage errors ranged from -2.76% to 8.75%. The largest errors occur for YC4 when the thicknesses of the top layer are closed to zero (i.e. the thickness of the top layer is equal to 0.1m) by overestimating infiltrated water based on Green-Ampt with effective soil parameters. In this case, infiltration rate by Richards equation is greater than the rate by Green-Ampt in the early part of the storm, because of relatively small value of effective hydraulic conductivity compared to $K_s$ of top layer. However, after the bottom layer begins to affect the infiltration process, the infiltration rate based on numerical solution become slightly less than the infiltration rate based on Green-Ampt method using effective soil parameters and relatively longer duration after this process makes estimating cumulative infiltrated water based on Green-Ampt using effective soil parameters overestimate.

The longer duration effect can be explained by comparing event YC1, YC2, YC3 and YC4 where the thickness of the top layer is 0.1m. Figure 4.11 show rainfall distribution and infiltration rate based on Richards equation with two layers and Green-Ampt method using effective soil parameters for each event. The infiltration rates are measured at X=105m, Y=400m of the model domain and these rates are affected by both rainfall and run-on from adjacent areas. In all cases, surface ponding occurs faster in Green-Ampt model than in Richards equation so that the simulation based on Richards equation has more infiltrated water in the early part of the storm event. However, because of longer duration effect, the bottom layer dominates infiltration process in the later part of the event so that the errors between simulations based on Richards equation and Green-Ampt method become higher compared to the event with relatively shorter duration. For example, the percentage errors of YC1, YC2, YC3 and YC4 in these cases are -0.28, 1.4, 4.83 and 8.75%, respectively.

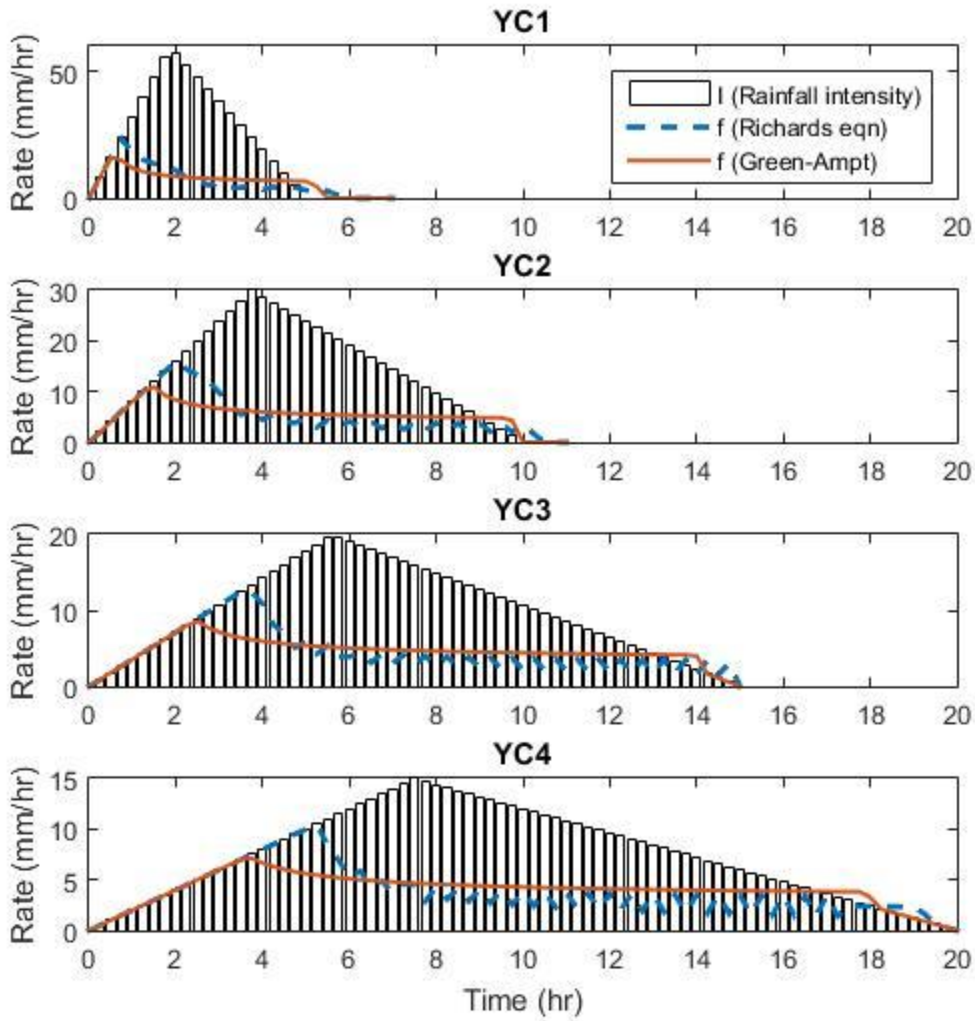


**FIGURE 4.11 RAINFALL DISTRIBUTION AND INFILTRATION RATE AT X=105M AND Y=400M FOR YC1, YC2, YC3 AND YC4 ($Z_{top} = 0.1m$)**

It is worth comparing events that have the same duration with different rainfall intensity. Figure 4.12 shows rainfall distribution and infiltration rates based on both Richards equation and Green-Ampt method using effective soil parameters for YC6, YC2, YC7 and YC8 where the thickness of top layer is 0.1m. These events have 10 hour durations with different rainfall intensity. YC6 has the lowest peak rainfall intensity and YC8 has the highest peak rainfall intensity among them. Although all estimations of cumulative infiltrated water of four events show good agreement with numerical solution, the errors show decreasing patterns from 3.72% for YC6 to -0.58% for YC8. These results show that the percentage errors can be affected by both rainfall intensity and its duration.

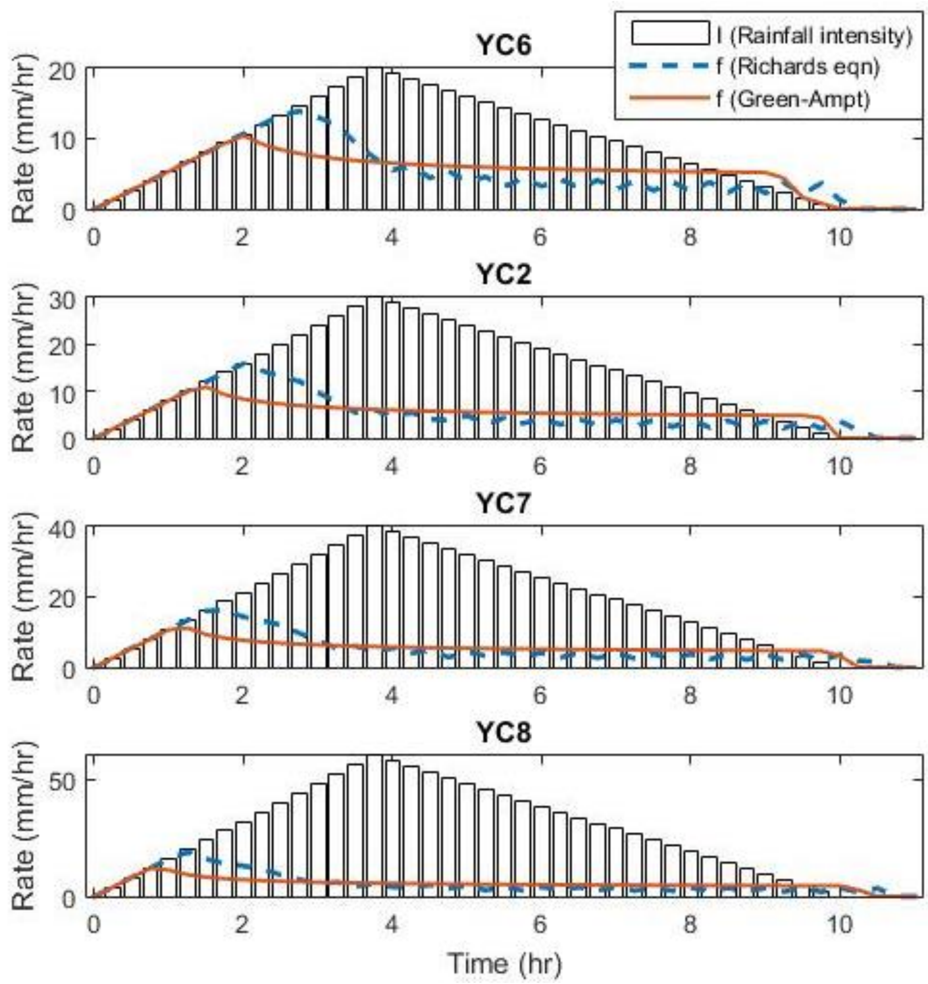


**FIGURE 4.12 RAINFALL DISTRIBUTION AND INFILTRATION RATE AT X=105M AND Y=400M FOR YC6, YC2, YC7 AND YC8 ($Z_{top} = 0.1m$)**

The total number of comparisons of accumulated water between Richards equation with two-layered soils and Green-Ampt method using effective soil parameters are 25 and among these cases, 22 cases have less than 5% of percentage errors under Yen-Chow hyetograph. These simulation results show that the approach to estimate infiltrated water for two-layered soil presented in this thesis also works well under unsteady rain and the simple and quick procedures can be useful for estimating cumulative infiltrated water for two-layered soils.

## 4.3. SUMMARY AND CONCLUSION

In this thesis, infiltration into coarse-over fine stratifications is discussed and simple and quick procedures for obtaining effective Green-Ampt parameters for two-layered soils are introduced by considering the maximum saturated depth, the hydraulic properties of both layers and the thickness of the top layer under both steady and unsteady rain. Especially, the hydraulic conductivity is considered as the most important hydraulic soil properties among three Green-Ampt soil parameters for infiltration process. The procedures discussed in this thesis consist of two steps.

First, simple ways to estimate the maximum saturated depth of the top layer for a given storm are presented by considering both rainfall characteristics and the hydraulic soil properties of top layer. Estimation of the maximum saturated depth of the top layer for a given event is important because the bottom layer does not affect infiltration process until the wetting front reaches the boundary of two layers. If the thickness of the top layer is greater than maximum saturated depth, considering only the top layer makes no difference in terms of infiltration process for a given storm. The comparison results show that the proposed estimation of the maximum saturated depth of top layer for a given storm shows good agreement with MIKE SHE simulation results based on Richards equation under both steady and unsteady rain.

Second, by using the maximum saturated depth of the top layer, the procedures to obtain effective hydraulic conductivity of two-layered soils with different layer thicknesses are presented. Under steady rain, there are three cases considered depending on rainfall intensity and soil properties of the top layer. The simulation results of accumulated water based on Green-Ampt method using effective soil parameters determined using the proposed method of two layers was compared to the simulation results based on Richards equation with two-layered soils. There were 16 cases of steady rain and the percentage errors ranged from -6.5 to 3.71%. For unsteady rain, Yen-Chow hyetograph is used to simulate MIKE SHE model. Eight different storm events are simulated to examine a wide range of rainfall intensity and storm duration. The maximum saturated depth of top layer is calculated for each event based on cumulative infiltrated water by using the modified explicit function of Green-Ampt method and effective hydraulic conductivity is estimated by considering both the maximum saturated depth of top layer and thickness of top layer. MIKE SHE simulation results of cumulative infiltrated water based on Green-Ampt method using effective soil parameters are compared with MIKE SHE simulation results based on Richards equation with two-layered soils with different depth of top layer. There are 25 different cases of different storm events and thicknesses of the top layer to compare and the percentage errors between two simulations ranged from -2.76 to 8.75%.

These results show that the proposed simple and quick procedures for estimating effective soil parameters show good agreement both under steady and unsteady storm events in terms of the cumulative infiltrated water.

Therefore, this approach will help researchers and engineers to save time and effort dealing with two-layered soils using Green-Ampt method. For cases where the bottom layer impacts infiltration process, considerable time and effort is needed to develop a model that simulates the infiltration considering both soil layers. In particular, developing a model based on Richards equation requires more detailed hydraulic soil properties and much longer computational time than a model based on Green-Ampt. Even though the proposed procedures presented in this thesis are limited to two-layered soils and coarse-over-find stratifications, the method developed herein is useful for determining the partitioning of rainfall into runoff and infiltrated water in two-layered soils by saving a lot of time and effort.

## 4.4. FUTURE RESEARCH AND SUGGESTIONS

The procedures to obtain effective Green-Ampt parameters for two-layered soils presented in this thesis are limited to a single storm event. Future research could build on the methods presented here to develop effective Green-Ampt parameters for continuous simulation. For example, future research could compare real hyetographs with Yen-Chow that match depth, duration, and first moment of rain. Since continuous simulation comprises many non-linear hyetographs, this comparison of Yen-Chow to a real storm is foundation that applies to design storm and then allows possibility of continuous simulation.

Furthermore, the procedures to estimate effective Green-Ampt parameters are also limited to two-layered soils. The procedures can be extended to multilayered soils with decreasing hydraulic conductivity. For example, if there were three layered soils and calculated maximum saturated depth exceeds the sum of thickness of upper top two layers, maximum saturated depth for upper top two layers could be recalculated using effective Green-Ampt soil parameters that approximates the behavior of upper two layers. Also, similar to the procedures presented here, effective Green-Ampt soil parameters for three layers could be estimated assuming upper two layers are a homogeneous soil with effective soil parameters.

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